NOTICE

All drawings located at the end of the document.

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DIST.	LTR	ENC
BARTHEL, J.M.		
BENGEL, P.R.		
BENSON, C.A.		
CARMEAN, C.H.		
DAWSON, D.		
EDWARDS, J.D.		
FINDLEY, M.E.		
FITZ, R.C.		
GUINN, L.A.		
HUGHES, F.P.		
McANALLY, J.L.		
POWER, A.P.		
REED, A.B.		
TYSON, A.M.		
WAGNER, M.J.		
WHEELER, M.		
CHROMEC, W	✓	✓
LAW, J	✓	✓
RMRS RECORDS (2)	X	X
RF CORRES. CONTROL	X	X
TRAFFIC		
PATS/T130G		

CLASSIFICATION:

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UNCLASSIFIED		
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☐ PARTIAL/OPEN
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LTR APPROVALS:

ORIG. & TYPIST INITIALS: JKH: CB

RF-46469(Rev.1/97)

MRS Rocky Mountain Remediation Services, L.L.C.
... protecting the environment
Flats Environmental Technology Site
x 464
, Colorado 80402-0464
(303) 966-7000

September 30, 1997

Christine Dayton
Kaiser-Hill, L.L.C.
T130C

EVALUATION OF EXISTING DATA ON ACTINIDE MIGRATION REPORT - JKH-018-97

Nineteen copies of the report, "Evaluation of Existing Data on Actinide Migration at the Rocky Flats Environmental Technology Site are attached. Per your request, the following copies have been made: Ten for Kaiser-Hill Community Relations, five for Kaiser-Hill internal distribution and four copies for the Department of Energy, Rocky Flats Field Office.

RMRS will distribute copies to the four Actinide Migration Panel members and to Dr. Greg Choppin.

John K. Hopkins
Manager
Site Closure

JKH:cb

Attachments:
As Stated

A-SW-002578

RF/RMRS-97-074.UN

SUMMARY OF EXISTING DATA ON ACTINIDE MIGRATION AT THE ROCKY FLATS ENVIRONMENTAL TECHNOLOGY SITE

SEPTEMBER, 1997

U.S. Department of Energy
Rocky Flats Environmental Technology Site
Golden, Colorado

REVIEWED FOR CLASSIFICATION
By R. S. Cichorz U/NU
Date September 15, 1997

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ACRONYMS

ALF	Action Level and Framework
Am	americium
BGCR	Background Geochemical Characterization Report
BSCP	Background Soils Characterization Program
BZ	Buffer Zone

CDPHE	Colorado Department of Public Health and the Environment
CEC	cation-exchange capacity
cfm	cubic feet per minute
COC	chemicals of concern
D&D	Decontamination and Decommissioning
DCG	derived concentration guide
DOE	Department of Energy
GIS	geographical information system
HPGe	High Purity Geranium
HSPF	Hydrological Simulation Program - FORTRAN
IA	Industrial Area
IM/IRA	Interim Measure/Interim Remedial Action
IMP	Integrated Monitoring Plan
ITS	interceptor trench system
LHSU	Lower Hydrostratigraphic Unit
MUSCLE	Modified USLE Model
NEA	European Nuclear Energy Agency
NORM	natural organic matter
NSD	New Source Detection
NWC	North Walnut Creek
POE	Point of Evaluation
Pu	plutonium
RAAMP	Radioactive Ambient Air Monitoring Program
RFCA	Rocky Flats Cleanup Agreement
RFEDS	Rocky Flats Environmental Database System
RFETS	Rocky Flats Environmental Technology Site
RFFO	Rocky Flats Field Office
RFI/RI	RCRA Facility Investigation/Remedial Investigation
RUSLE	Revised USLE Model
SCSCR	Soil Conservation Service Curve Number
SID	South Interceptor Ditch
SWC	South Walnut Creek
SWMM	Storm Water Management Model
SRM	Sediment Removal Model
TIMS	thermal ionization mass spectrometry
TSP	total suspended particulates
TSS	Total Suspended Solids
U	uranium
UHSU	Upper Hydrostratigraphic Unit
USLE	Universal Soil Loss Equation
WWTP	Waste Water Treatment Plan

1.0 INTRODUCTION

The evaluation of remedial alternatives for actinides (herein considered as plutonium [Pu], americium [Am], and uranium [U] isotopes) at the Rocky Flats Environmental Technology Site (RFETS) (the "Site") must consider migration and mobility (i.e., transport) along environmental pathways. Transport pathways include: soil (surficial and subsurface), sediment, groundwater, surface water, and air. During 1996, an Actinide Migration Expert Panel was convened by the Department of Energy, Rocky Flats Field Office (DOE, RFFO). The Panel, which consisted of nationally-recognized specialists on actinide chemical behavior and migration/mobility in the environment, reviewed existing data on actinide migration at RFETS, and made recommendations for further work. Their recommendations included: 1) develop a defensible conceptual model for actinide transport, based on a thorough understanding of chemical and physical processes; 2) investigate the long-term impacts of actinide geochemical mobility on remedial requirements; and 3) evaluate the long-term protectiveness of the Rocky Flats Cleanup Agreement (RFCA), Attachment 5, Action Levels and Standards Framework for Surface Water, Groundwater, and Soils (ALF)(DOE, 1996) soil action levels.

This report presents a summary of existing data that has been initiated to further the understanding of the conceptual model as recommended by the Panel. An update to the *Development of Conceptual Model of Potential Pathways for Migration of Actinides Uranium, Plutonium, and Americium at RFETS* included in the *Proposed Path Forward for the Actinide Migration Studies* (DOE, 1997a) is developed in this report to better understand the relationship among the transport pathways and the potential effects of actinides on surface water and air quality.

1.1 PURPOSE AND OBJECTIVES

Over the past two decades, routine monitoring and studies of environmental media at RFETS have shown that site-derived actinides have been released and are present in the environmental media at RFETS. DOE, RFFO and the Kaiser-Hill Team have initiated multi-year Actinide Migration Studies which include summarizing the diverse body of existing data, evaluating the protectiveness of soil action levels on surface water quality, and providing additional data on actinides in the Site's environment as required for remedial action. This work supports the Site's Closure Plan *Accelerating Cleanup: Focus on 2006* (DOE, 1997b) that was developed to achieve accelerated risk reduction and significant cleanup of the Site by calendar year 2006.

The purpose of this report is to develop a better understanding of the chemical and physical mechanisms of actinide mobility and potential impacts to surface water by summarizing existing knowledge on actinide behavior and distribution in soils, groundwater, and surface water. This information will better the understanding of the actinide migration conceptual model (DOE, 1997a) and identify additional data required for designing remedial actions.

1.2 REGULATORY FRAMEWORK

The ALF sets forth standards and action levels for environmental media. These standards and action levels incorporate the RFCA Vision, and land- and water-use controls in the RFETS cleanup. Actinide surface water standards (0.15 pCi/L each, for plutonium and americium) are based upon human health risk as a consequence of human ingestion of surface water and are assigned at compliance points as water leaves the site, so that the surface water is of acceptable quality for all designated uses. The Site's water quality standard for uranium is currently set at 10 pCi/L based on ambient levels in Site surface waters. The State of Colorado has suspended consideration of a statewide health based standard until the Environmental Protection Agency promulgates a maximum contaminant level for uranium in drinking water. The soil action levels for radionuclides are based upon radiation dose limits for designated land-use scenarios for RFETS. The soil action levels did not consider the transport of soil containing actinides to surface water because it was assumed, when the soil action levels were calculated, that there would be no consumption of groundwater or surface water. The soil radionuclide action levels must be assessed for long-term protectiveness of surface water. The RFCA states that: "protection of surface water uses with respect to the long-term Site condition will be the basis for making soil and groundwater remediation and management decisions, and that additional groundwater or soil remediation or management may be required for the protection of surface-water quality or ecological resources."

1.3 SCOPE OF THE REPORT

This report supports the mission and goals of the Actinide Migration Studies by presenting actinide data compiled from the Rocky Flats Environmental Database System (RFEDS), RCRA Facility Investigation/Remedial Investigation (RFI/RI) reports, Interim Measure/Interim Remedial Action (IM/IRA) decision documents, and the results of other reports and studies on the behavior of actinides in the RFETS environment. The current state of knowledge is summarized using available information with respect to the distribution and transport of actinides in surface soil, subsurface soil, sediment, groundwater, surface water, and air at RFETS. Data deficiencies are identified, and recommendations for future actions are made.

This report reviews and summarizes the diverse body of existing data on actinides in the RFETS environment and identifies existing deficiencies in knowledge of actinide behavior in soils, groundwater, and surface water. The *Proposed Path Forward for Actinide Migration* (DOE, 1997a) proposes actions that will facilitate the development of the conceptual model, providing a better understanding of the relationship of actinide levels in soil, and the effects of remedial activities on the long-term protection of surface water.

1.4 REFERENCES

DOE, 1996, Rocky Flats Cleanup Agreement, July 19, 1996.

DOE, 1997a, Proposed Path Forward for the Actinide Migration Studies, June, 1997.

DOE, 1997b, Accelerating Cleanup: Focus on 2006, June, 1997.

2.0 BACKGROUND

The following sections present the geologic, hydrogeologic, and climatologic setting; actinide source areas; and a summary of previous actinide investigations at RFETS relative to the occurrence and transport pathways of actinides in the environment.

Environmental conditions influence the mode, rate, and direction of contaminant transport and, to a large extent, determine the chemical fate of contaminants in the environment. Chemical and physical interaction of various environmental media can play an important role in mobilizing or demobilizing the spread of contamination, which must be understood in order to evaluate and design appropriate remedial actions. For additional discussion of these media, the reader should consult the 1994 RFETS *Environmental Report* (Kaiser-Hill, 1995) and the 1995 RFETS *Sitewide Geoscience Characterization Study* series of reports, including the *Geologic Characterization Report* (EG&G, 1995b), *Hydrogeologic Characterization Report* (EG&G, 1995c), and *Groundwater Geochemistry Report* (EG&G, 1995a). A discussion of potential actinide transport pathways and their interaction is further described in Section 8.

A summary of previous investigations provides insights into work done to date on actinide migration at RFETS.

2.1 CLIMATOLOGY

Basic climatological information (including general descriptions of the climate, precipitation, temperatures, and wind patterns) is pertinent to understanding the hydrologic setting and actinide migration potential of environmental media at RFETS. The local climate at RFETS exerts a strong influence on soil, groundwater, and surface water conditions. For example, precipitation amount, frequency, intensity, and seasonality (combined with air temperatures, humidity, and wind conditions) influence the potential for wind and soil erosion, groundwater recharge, and evapotranspiration. These parameters will be discussed briefly to provide background information for the hydrology sections of the report. A more detailed summary of the climatology and meteorology at the Site is provided in *RFETS Environmental Report* (Kaiser-Hill, 1995).

The RFETS area has a semi-arid climate that is characteristic of much of the central Rocky Mountain region. Table 2-1 summarizes climatic data for the Site collected in 1994. Historically, annual precipitation at Rocky Flats averages nearly 15.5 inches, with about 42% of the annual precipitation falling during the spring season (April through June) (EG&G, 1995c). Precipitation falls primarily as snow from late October through early April and as rain during the remaining months. The Site is less prone to severe weather activity than the plains to the east because of its locality close to the foothills. Thunderstorms initiated over the foothills usually intensify as they move eastward into the more humid and unstable air mass over the eastern plains of Colorado. Tornado formation over RFETS is very unlikely (Kaiser-Hill, 1995). The thin, dry atmosphere results in wide diurnal temperature ranges, with strong daytime warming and nighttime cooling. Temperatures are generally moderate, but short periods of exceptionally warm or cold weather resulting from incursions of hot southwestern desert or frigid Canadian air masses are possible during the mid-summer and mid-winter months. Temperature ranges, averages, and extremes for the Site in 1994 are presented in Table 2-1 (Kaiser-Hill, 1995).

High-wind events, known as chinooks, are common along the Front Range during the winter and early spring months. Wind gusts will typically exceed 70 miles per hour (mph) several times in a normal year. In the strongest gusts, winds have exceeded 100 mph. Wind directions most frequently are from the west-southwest through northerly directions, with the strongest gusts originating from the west-northwest and west. Wind speeds above 18 mph occur primarily with westerly winds and, to a lesser extent, northerly winds. A summary of 1994 wind directions and wind-speed frequencies measured at a 10-meter height at the Site is provided in Table 2-2 and is shown graphically by a wind rose diagram in Figure 2-1 (Kaiser-Hill, 1995).

Table 2-1. Summary of Meterological Data for 1994

1994 Annual Climatic Summary

Temperatures (°F)

Month	Means High	Means Low	Average	Extremes High	Date	Low	Date	Mean Dew Point (°F)	Mean. Rel. Humidity (%)
January	44.6	18.5	31.6	60.1	23	-5.4	31	10.4	45.2
February	44.0	14.7	29.4	61.0	16	-2.6	8	12.8	55.0
March	54.3	25.4	39.9	68.7	14	5.7	9	19.8	51.3
April	56.7	31.3	44.0	78.3	23	18.1	5	28.0	61.1
May	72.4	43.7	58.1	87.3	30	32.0	2	40.1	54.8
June	84.7	51.8	68.3	101.0	26	38.7	9	41.1	45.1
July	85.3	52.8	69.0	94.1	10	42.4	7,8	43.6	45.8
August	84.8	55.3	70.1	95.0	6	49.1	20	47.7	51.4
September	78.1	48.2	63.1	90.1	10	24.4	22	34.8	34.1
October	61.1	36.1	48.6	75.3	11	26.0	30	30.4	50.8
November	46.7	22.4	34.6	68.8	7	8.7	19	16.8	50.2
December	47.0	21.1	34.0	66.0	1	-4.0	31	11.7	39.7
Annual	63.3	35.1	49.2	101.0	6/26	-5.4	1/31	28.1	48.7

Month	Wind Speed (mph) Mean	Wind Speed (mph) Peak	Atmos. Pressure Mean (mb)	Solar Total kW h/m^2
January	12.8	85.4	810.9	81.1
February	10.7	94.8	807.8	101.3
March	8.9	72.0	811.4	145.2
April	9.1	67.3	810.8	137.8
May	8.9	57.0	812.9	201.2
June	8.4	42.7	814.4	224.9
July		76.9	816.8	201.5
August	8.6	62.2	817.7	171.9
September	8.7	56.4	816.7	152.7
October	9.4	61.4	811.7	118.6
November	10.0	75.5	808.1	93.0
December	9.5	93.4	811.2	71.0
Annual	9.5	94.8	812.5	141.7

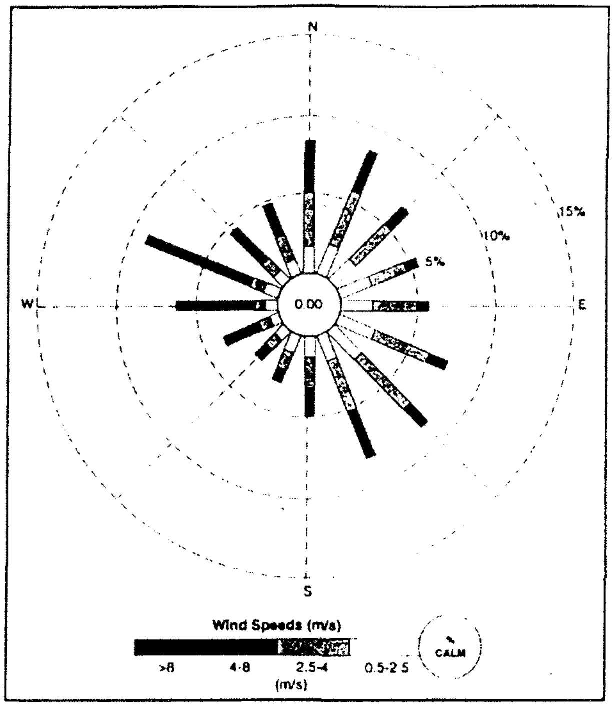
Month	Precipitation (inches) Total	Daily Max.	Date	15-Min. Max.	Snowfall Inches	Number of Days Precip. ≥0.10"	Max. Temp. ≥90°F	Min. Temp. ≤32 °F
January	0.45	0.2	26	0.0	7.5	0.0	0.0	30.0
February	0.76	0.4	28	0.0	9.4	3.0	0.0	27.0
March	1.05	0.4	28	0.0	11.5	4.0	0.0	24.0
April	2.46	0.5	25	0.1	24.5	7.0	0.0	18.0
May	1.37	0.4	13	0.2		5.0	0.0	1.0
June	1.12	0.4	22	0.1		4.0	9.0	0.0
July	0.4	0.1	31	0.0		1.0	9.0	0.0
August	1.51	0.6	10	0.3		5.0	8.0	0.0
September	0.68	0.5	21	0.1	5.0	2.0	2.0	2.0
October	0.96	0.4	17	0.1	3.0	2.0	0.0	7.0
November	1.08	0.4	8,13	0.2	18.0	4.0	0.0	27.0
December	0.16	0.0	6	0.0	11.5	0.0	0.0	29.0
Annual	12.0	0.6	8/10	0.3	90.4	37.0	28.0	165.0

Table 2-2. Wind Data Summary for 1994

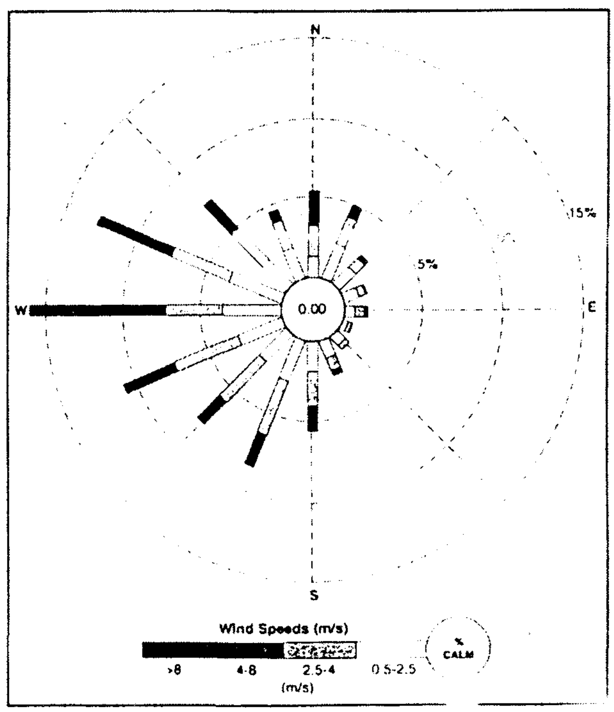
Site Wind Direction Frequency (Percent) by Four Wind-Speed Classes

(15 - Minute Averages - Annual 1994)

	Calm <0.5 m/s (<1.1 mph)	0.5 - 2.5 m/s (1.1 - 5.6 mph)	2.5 - 4.0 m/s (5.6 - 9.0 mph)	4.0 - 8.0 m/s) (9.0 - 18 mph)	>8.0 m/s (>18 mph)	Total %
	2.2					
N	-	1.55	2.60	2.57	0.15	6.87
NNE	-	1.63	2.21	1.55	0.14	5.53
NE	-	1.36	1.85	0.87	0.02	4.10
ENE	-	1.42	1.41	0.48	0.01	3.32
E	-	1.27	1.62	0.49	0.02	3.40
ESE	-	1.42	1.94	0.68	0.01	4.05
SE	-	1.66	2.32	0.82	0.02	4.82
SSE	-	1.40	2.11	1.70	0.22	5.43
S	-	1.59	2.03	1.54	0.13	5.29
SSW	-	1.67	2.08	1.52	0.10	5.37
SW	-	1.50	2.03	2.25	0.22	6.00
WSW	-	1.79	2.94	3.32	0.95	9.00
W		2.00	2.46	2.69	3.00	10.15
WNW	-	1.88	2.33	4.00	3.82	12.03
NW	-	1.49	2.00	2.35	0.53	6.37
NNW	-	1.35	2.21	2.51	0.10	6.17
TOTALS	2.20	24.98	34.14	29.34	9.44	100.00



Rocky Flats 1994 Windrose - Day



Rocky Flats 1994 Windrose - Night

Figure 2-1. 1994 Wind Speed and Direction

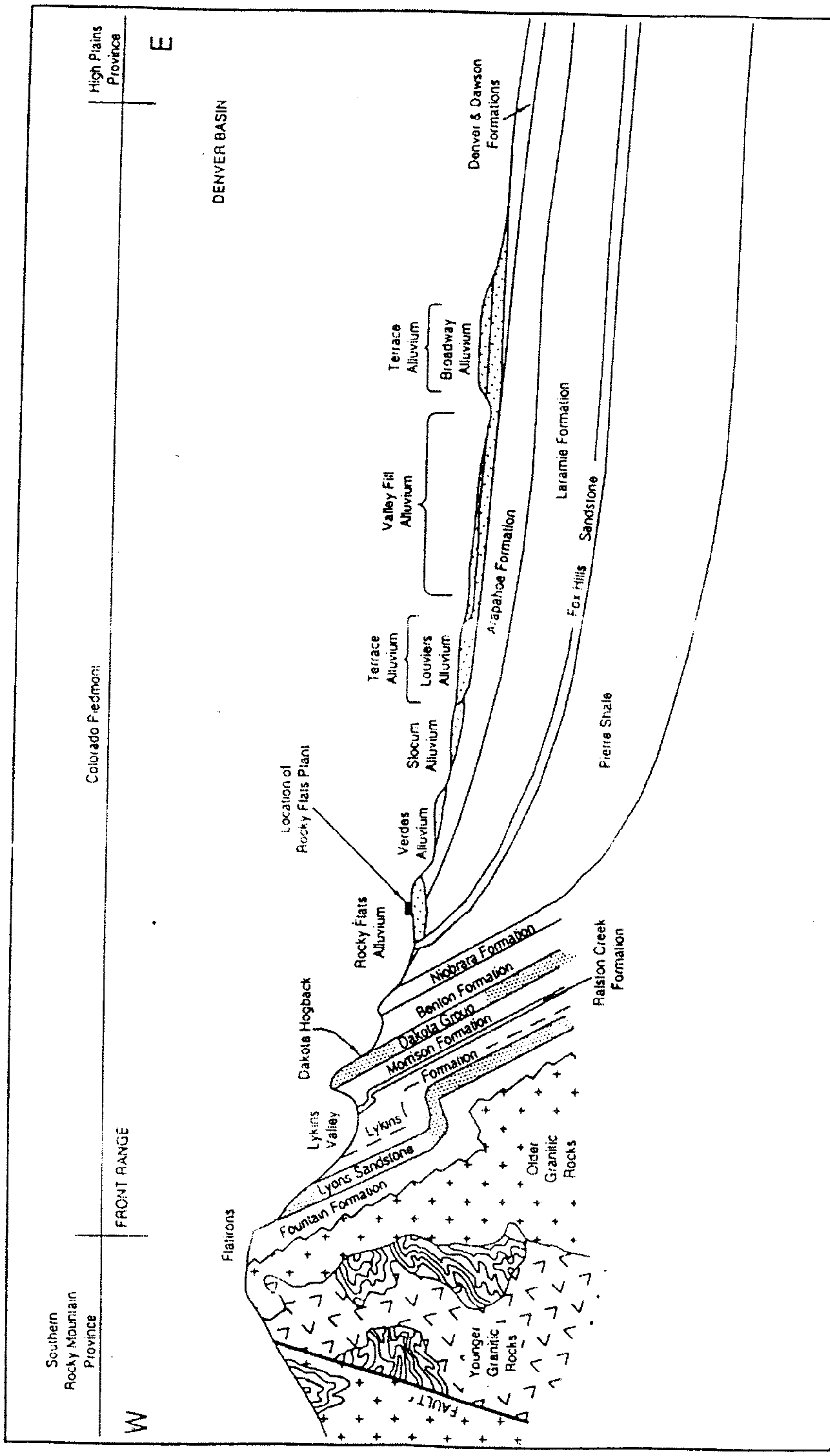
2.2 GEOLOGY

At an elevation of 6,000 feet above mean sea level, RFETS is located on the Colorado High Plains approximately two to six miles east of the Front Range mountain front. Geologic units at RFETS can be grouped into two general categories: unconsolidated Quaternary surficial deposits and underlying consolidated Cretaceous bedrock (EG&G, 1995b). Figure 2-2 is a generalized geologic cross section that illustrates the surficial and bedrock materials within each group.

Prior to the deposition of Quaternary surficial deposits, the gently eastward-dipping Cretaceous-age bedrock in the Rocky Flats area was subjected to erosion that produced a broad, flat erosional surface (a peneplain). During the Pleistocene, this bedrock surface was subsequently overlain by a blanket of alluvial fan deposits, known as the Rocky Flats Alluvium, that were derived from Coal Creek Canyon (EG&G, 1995b). Headward erosion by westward progressing drainages has since incised both the Rocky Flats Alluvium and the underlying bedrock peneplain. Approximately half of the surface area covered by RFETS has been incised, removing the Rocky Flats Alluvium. In most areas, these erosional surfaces have been subsequently covered by stream sediments or colluvium. A summary of the stratigraphic profile is presented in the following sections. Younger units are described first, followed by progressively older, deeper units.

2.2.1 Unconsolidated Deposits

The surface of RFETS is covered almost entirely by an extensive layer of unconsolidated Quaternary deposits consisting of Holocene colluvium and valley-fill alluvium, and Pleistocene Rocky Flats Alluvium. Holocene slump and landslide material are also present locally on valley slopes and indicate that mass movement is an important, albeit slow, erosional agent in areas of RFETS.



Not to Scale
Source: Boulder County [illegible] Commission 1983 and Scott 1960

PREPARED FOR
U.S. DEPARTMENT OF ENERGY
ROCKY FLATS ENVIRONMENTAL TECHNOLOGY SITE
GOLDEN, COLORADO

FIGURE 2-2
GENERALIZED EAST-WEST CROSS SECTION
FRONT RANGE TO DENVER BASIN

Colluvial deposits, which are present on the valley slopes in the central portion of RFETS, were derived from geologic material exposed on the steep slopes and topographic highs and were formed by slope wash and downslope creep. The colluvium ranges in thickness from 0 to 20 feet, with the thickest sequences occurring at the base of the valley slopes. The colluvium is composed of clay, clayey gravels, and lesser amounts of sand and silt. Slump and landslide deposits were derived from the colluvium and Rocky Flats Alluvium, and are most common on valley slopes along the Rock Creek and Walnut Creek drainages in the northern portion of RFETS. Valley-fill deposits were fluvially-derived from upstream materials, and consist of clay, silt, and sand with lenses of gravel. These deposits occur along the drainage bottoms in and adjacent to stream beds, and are most common in the eastern portions of RFETS. Thicknesses range from 0 to 25 feet (EG&G, 1995b).

Pleistocene deposits consist primarily of the Rocky Flats Alluvium, which is the most prevalent unconsolidated surficial deposit at RFETS. The Rocky Flats Alluvium ranges in thickness from 0 to 100 feet and forms a broad layer that extends across most of the western portion of RFETS (EG&G, 1995b). The deposit is comprised of poorly sorted, clayey gravels, and sands with abundant cobble and boulder-sized material and discontinuous lenses of clay, silt, and sand. Caliche, a pedogenic deposit of calcium carbonate, is found discontinuously in the Rocky Flats Alluvium, but tends to be better developed and more abundant from the western end of the Industrial Area (IA) eastward to the margin of the Rocky Flats Alluvial Fan. Significant quantities (up to 25 to 80% by volume) of caliche are present in some stratigraphic intervals of the Rocky Flats Alluvium (EG&G, 1995b). Caliche horizons are most commonly encountered within 10 feet of the ground surface.

2.2.2 Consolidated Bedrock Deposits

The unconsolidated surficial deposits unconformably overlie the claystone, siltstone, and sandstone bedrock of the Upper Cretaceous Arapahoe and Laramie Formations. The Arapahoe Formation ranges from 0 to 50 feet thick at RFETS and has been shown to contain a mappable, but discontinuous, fine- to medium-grained basal sandstone unit. This unit has been designated the Arapahoe (or Number 1) Sandstone (EG&G, 1995b) and is known to subcrop beneath the Rocky Flats Alluvium and Colluvium in the 903 Pad, East Trench, and other areas of the eastern IA. It consists primarily of an argillaceous, fine- to medium-grained, locally conglomeratic, moderately- to poorly-sorted sandstone that ranges in thickness from 0 to less than 50 feet (EG&G, 1995b). Calcite cement, found in some deeper Laramie Formation sandstone layers, is absent in the Arapahoe Formation Sandstone.

The Arapahoe Formation Sandstone is the uppermost sandstone of significant lateral extent, and has been shown to be a pathway for lateral transport of contaminated groundwater.

The Laramie Formation conformably underlies the Arapahoe Formation and is approximately 600 to 800 feet thick. The Laramie Formation is subdivided into two members. The upper member of the Laramie Formation is 500 to 600 feet thick and consists primarily of massive claystone, and siltstone. The lower member is about 300 feet thick and is composed of sandstones, claystones and coal beds. The upper member is generally much finer-grained than the lower member, but contains several separate and discontinuous clayey sandstone units historically designated as the No. 2 through No. 5 Sandstones (EG&G, 1995b). Unlike the Arapahoe Formation sandstone, these sandstone units exhibit lithologic and hydrologic characteristics (i.e., high matrix clay content and low permeability) that are not indicative of groundwater flow pathways. These lenticular Laramie Formation sandstones are texturally distinct from the Arapahoe Formation sandstone by virtue of their high silt and clay content (EG&G, 1995b).

The Upper Cretaceous Fox Hills Sandstone conformably underlies the Laramie Formation and ranges from 90 to 140 feet in thickness. In general, the Fox Hills Sandstone is a very fine- to medium-grained, angular to subrounded, well-sorted silty sandstone. The Fox Hills Sandstone is an aquifer of regional significance, which lies at a depth of 700 to 800 feet below ground surface at RFETS. Underlying the Fox Hills Sandstone are several thousand feet of the Lower Cretaceous Pierre Shale and older units (EG&G, 1995b).

Lithologic logs from boreholes drilled into bedrock indicate the presence of a weathered zone in the upper portion of the bedrock. Fracturing and weathering increase the permeability of bedrock material. The weathered zone is commonly less than 15 feet thick, but may be as thick as 60 feet. The thickness of the weathered bedrock zone is dependent on factors such as relative abundance of fractures, lithology, elevation relative to the water table, and proximity to valley bottoms.

2.2.3 Structural Features

The bedrock strata exposed immediately west of RFETS has been folded into steeply eastward-dipping exposures of the Fox Hills Sandstone and Laramie Formations. These units receive recharge from precipitation along the exposed hogbacks northwest and southwest of RFETS. The formations also receive recharge from the overlying Rocky Flats Alluvium and Arapahoe Formation.

Small-scale structural features such as joints and fractures are present in the bedrock units. Joint and fracture surfaces are commonly coated with secondary iron and manganese oxides and hydroxides in the weathered portion of the bedrock units. Slickensides are also present on some fracture surfaces. The presence of such features increases secondary porosity and permeability and indicate that groundwater flow is probably enhanced in the weathered portion of the bedrock. Several bedrock faults have been identified in the RFETS IA; however none have been observed to offset alluvial materials (EG&G, 1995b). The available hydrogeologic and geochemical data indicate that fractures and faults are not significant conduits for downward vertical groundwater flow to the Laramie-Fox Hills deep aquifer (RMRS, 1996).

2.3 HYDROGEOLOGY

2.3.1 Hydrostratigraphy

Shallow groundwater flow systems at RFETS have been categorized into two hydrostratigraphic units based on contrasts observed between groundwater geochemistry, core logging, and hydraulic conductivity determinations (EG&G, 1995c). This division basically reflects the relative degree of hydrologic activity experienced by the units - the uppermost unit being the more active and transmissive of the two. The upper hydrostratigraphic unit (UHSU) consists of the distinct lithologic units of the Rocky Flats alluvium, colluvium, valley-fill alluvium, landslide deposits, weathered Arapahoe and Laramie Formation bedrock, and any sandstone units within the Arapahoe and Laramie Formations that are in hydraulic connection with the overlying unconsolidated surficial deposits or with the ground surface. The lower hydrostratigraphic unit (LHSU) is composed of the unweathered bedrock of the Arapahoe and Laramie Formations. This unit forms a thick (several hundred feet), regionally extensive confining layer that serves to isolate shallow groundwater from the underlying Laramie-Fox Hills aquifer (RMRS, 1996).

2.3.2 Groundwater Occurrence and Flow Conditions

Groundwater is found in all geologic units present at RFETS, although not always in predictable amounts and availability. In UHSU deposits, the quantity of water in storage at any particular locality varies widely and is a function of bedrock topography, proximity to drainages, seasonality, and local sources of recharge. The saturated thickness of UHSU alluvium is greatest in the western portion of RFETS (>40 feet) and thinnest along hillsides and in the eastern portion of the site. Areas of thin saturation commonly contain regions of discontinuous, seasonally-unsaturated alluvium due to irregularities in bedrock topography and water table fluctuations. Depth to shallow groundwater varies anywhere from 0 feet at flowing seepage areas to 70 feet at the west end of the Site. The depth to water is generally shallowest in areas of thinner surficial deposits, such as the IA, margins of the Rocky Flats Alluvium, and creek drainages. Average depth to water and saturated alluvial thickness at the 903 Pad and Lip Area is on the order of 10 and 5 feet, respectively (EG&G, 1995c).

Seasonal fluctuations in shallow groundwater levels are observed in monitoring wells across the Site and normally range from 3 to 6 feet (EG&G, 1995c). Larger annual fluctuations have been recorded at several locations in and adjacent to the IA, with some wells exhibiting water level rises of over 10 feet. Well hydrographs indicate that water levels normally peak in May or June shortly following the spring rain season. Hydrographs of many older Rocky Flats Alluvium wells (installed 1986 and 1987) indicate that base water levels over the past decade have generally declined 1 to 5 feet, possibly as a result of changes in water management practice at the plant.

In a broad sense, the dramatic response of groundwater levels measured in many UHSU wells during the spring and early summer of 1995 was as noteworthy, though less apparent, as that observed for surface flow conditions. Record high water levels were recorded in many wells during and following the exceptionally wet spring of 1995. Water level rises in the range of 15 to 20 feet were observed in some wells located in the IA, East Trenches, and eastern Buffer Zone (BZ) Areas. Flowing artesian well conditions were noted at several well points that monitor seeps at the Solar Pond and southern IA. The rapid rate of decline observed in some well hydrographs was almost equal to the rate of rise, suggesting that lateral subsurface drainage was rapid and probably more extensive than expected in normal years.

The magnitude of these rises, when compared to ground surface elevations, indicates that a condition of temporary, complete to near-complete saturation (groundwater flooding) probably formed locally in areas of thin to moderately thick surficial deposits. In areas of recharge, such as all upland areas occupied by the Rocky Flats Alluvium and the majority of colluvium-covered hillslopes, the presence of saturated conditions indicates that the capacity of the geologic material to accept and transmit recharge water has been exceeded. The direction of soil water movement recharged from incident precipitation and runoff is initially downward until it reaches the water table and is transported laterally to a point of discharge. In comparison, groundwater discharge areas, such as hillside and stream channel seeps, are typified by saturated conditions that result in groundwater contact with surface soils. The potential significance of these two very different flow regimes on surficial and shallow subsurface soil actinide remobilization is reviewed in Section 2.3.4 and the Conceptual Model (Section 9).

The geology of the area exerts a controlling influence on groundwater flow due to the existence of sharp lithologic contrasts in the vertical distribution of geological materials (coarse-grained surficial deposits underlain by fine-grained bedrock) and the resulting bedrock topographic surface configuration. The predominantly claystone bedrock impedes the downward vertical migration of groundwater and directs flow laterally through the unconsolidated surficial and weathered bedrock materials. Groundwater flow tends to follow the bedrock surface and emerges as seeps, drain into the hillside colluvium, or migrates vertically into permeable subcropping sandstone units. In thinly-saturated areas, the bedrock surface plays a critical role in directing groundwater flow and, where locally high, in the development of unsaturated zones in unconsolidated surficial deposits. Groundwater in the UHSU regionally flows eastward from broad areas of recharge (located upgradient and on nearby topographic highs) toward the erosional limit of the Rocky Flats Alluvium, and then directly toward creeks in the drainage bottoms. After groundwater enters the valley-fill alluvium from the hillslopes, it flows eastward in the direction of stream flow and exits the site at the RFETS east boundary (Indiana Street).

2.3.3 Hydraulic Conductivities

In general, the UHSU at RFETS has a low to moderate hydraulic conductivity and typically yields small amounts of water to monitoring wells. Hydraulic testing of the wells indicates that the UHSU exhibits a wide range of hydraulic conductivities because of the diverse nature of the individual geologic materials that comprise the unit. Values of hydraulic conductivity range from as high as 5 x 10^{-2} centimeters per second (cm/sec) in localized areas of the valley-fill and Rocky Flats Alluvium, to as low as 7 x 10^{-8} cm/sec in the clay lenses of the Rocky Flats Alluvium (EG&G, 1995c). Hydraulic conductivities in the weathered bedrock portion of the UHSU range from 9.2 x 10^{-3} to 3 x 10^{-8} cm/sec - the highest values being associated with the Arapahoe Formation Sandstone and the lowest values being associated with weathered claystone bedrock. Colluvial deposits indicate a range of 9.3 x 10^{-4} to 4.0 x 10^{-6} cm/sec. Average values, calculated as geometric means, are 4.3 x 10^{-5} cm/sec for the colluvium; 2.1 x 10^{-4} cm/sec for the Rocky Flats Alluvium; and 2.5 x 10^{-3} cm/sec for the valley-fill alluvium in Woman Creek and Walnut Creek, respectively (EG&G, 1995c).

Hydraulic conductivities of LHSU materials are significantly lower than those of the overlying unit, with values ranging from 10^{-6} to 10^{-8} cm/sec in the unweathered claystone bedrock. Discussion of LHSU hydraulic conductivities is presented in more detail in RMRS (1996).

2.3.4 Groundwater Interaction with Surface Water and Soils

As described later in Section 5.0, the importance of groundwater as an actinide transport medium is limited to areas of contact with soils and surface water that contain actinide levels which exceed RFCA action levels. Groundwater is in direct connection with these media only immediately downgradient of areas where the water table intersects the ground surface. This requirement is met at hillside seeps and along stream beds containing valley-fill alluvial deposits such as depicted in Figure 2-3.

The pattern of seep distribution confirms that seep occurrence is controlled by local geologic conditions. Hillside seeps at RFETS are common along the eastern extent of the Rocky Flats Alluvium where the contact between the Rocky Flats Alluvium and underlying claystone subcrops along the upper margin of stream drainage valleys. In general, seeps occur in greater number and areal extent along the north side of the pediment ridges, as observed along South Walnut Creek and Rock Creek. Most seeps are ephemeral in nature and only discharge at the ground surface in the spring. Perennial seeps are relatively rare, with most located in the Rock Creek drainage. Groundwater seepage also occurs along segments of the Woman Creek stream channel, particularly above the Woman Creek stream diversion structure at Pond C-2, as determined from a stream gain/loss study (Fedors and Warner, 1993). The stream channels of North and South Walnut Creeks are so extensively interrupted by impoundments that channel seepage measurements have not been attempted nor are they expected to yield meaningful data.

Seep flow data are generally unavailable due to difficulties inherent with measuring broad, diffuse sources of discharge. The results of an incomplete seepage inventory conducted after the 1995 spring recharge event in portions of the Woman, Walnut, and Rock Creek watersheds revealed that, of over 200 potential seep areas indicated by wetland vegetation, only 32 had a measurable flow and, of these, 14 had flows of 1 gallon per minute or less. The remaining sites were moist to wet at the ground surface with little or no evidence of surface flow. Given the magnitude of the spring recharge event as reflected by sitewide high water table conditions, it is likely that seep flows measured during this time were at or near maximum levels. It was commonly observed during this survey that surface flow from many ephemeral hillside seeps percolate back into the soil below the discharge point before entering a surface water body. Direct contact with surface water may occur during exceptionally wet periods as a result of increased seep flow caused by abnormal water table rises or by mixing with surface runoff.

The most common type of seep develops at the contact between the Rocky Flats Alluvium and underlying bedrock claystones. These seeps are thought to be related to preferential flow channels in bedrock surface topography and/or alluvial stratigraphy (high hydraulic conductivity zones) (EG&G, 1995c). In the 903 Pad and East Trenches Areas, some seep occurrences have been attributed to discharge from the subcropping Arapahoe Formation sandstone which receives recharge from the overlying surficial deposits (EG&G, 1995c). The most notable sandstone seeps in this area include a grouping of seeps situated above the B-1 pond in the South Walnut Creek drainage and the 903 Pad Hillside seep located at the soil study area in the Woman Creek drainage.

Examination of the most recent sitewide seep location map (EG&G, 1995c, Plate 9) indicates that there are fewer seeps in the 903 Pad and east BZ Areas relative to adjacent hillslopes located to the west and north. Along the north slope of Woman Creek from the 903 Pad eastward to Indiana Street, evidence of present-day seep activity is limited primarily to the 903 Pad hillside seep and potentially a few scattered small seeps. Periodic activation of a series of presumably old seepage sites located east of the 903 Pad have occurred from historic spray evaporation operations conducted at the South Spray field; however, these sites have since returned to a dry state following cessation of spray field operations. As shown on Figure 2-3, sites for groundwater interaction with surficial soils and surface water are both limited in extent and predictable based on the high degree of hydrologic control exerted by the local geology.

Groundwater discharge to surface water is presumed to occur along major stream channels although relatively little information is available to evaluate the significance of this interaction. Stream gain/loss studies conducted along Woman Creek (EG&G, 1995c) have indicated that the flow regime in the upper reaches of the creek (west of confluence with Antelope Springs Creek) tend to be predominantly gaining while the lower reaches (east of Antelope Springs Creek) tend to be predominantly losing. The presence of gaining segments found just upstream of Ponds C-1 and C-2 suggest that these impoundments exert a local influence on groundwater discharge to surface water in the alluvium. Similar relationships are suspected to occur in the Walnut Creek drainage, but to an unknown degree because gain/loss stream flow data is lacking in this area. It can be assumed, however, that groundwater/surface water interactions are potentially more complex in North and South Walnut Creeks owing to the influence of plant discharges and a more extensive system of ponds and other stream channel modifications.

2.4 SURFACE WATER HYDROLOGY

Streams and seeps at RFETS are largely ephemeral, with stream reaches gaining or losing flow depending on the season and precipitation amounts. Surface water flow across RFETS is primarily from west to east, with three major drainages traversing the site. Fourteen detention ponds (plus several small stock ponds) collect surface water runoff, although only ten ponds require active management. Descriptions of the Site drainages and detention ponds, including their respective interest to this report, are contained below and shown in Figure 2-4.

2.4.1 Rock Creek

The Rock Creek drainage covers the northern portion of the RFETS BZ. The drainage channel is characterized by flat areas to the west, several small stock ponds within the creek bed, and multiple steep gullies and stream channels to the east. This basin is topographically isolated from the developed areas - it receives no runoff from IA and contaminant transport by surface (or subsurface) processes is not suspected. Analytical data for Rock Creek is not presented in this report.

2.4.2 Walnut Creek

Walnut Creek drains the central third of RFETS, including the majority of the IA. It consists of several tributaries (McKay Ditch, No Name Gulch, North Walnut Creek, and South Walnut Creek) which join prior to leaving RFETS at the eastern boundary (Indiana Street). East of Indiana Street, Walnut Creek is diverted by the Broomfield Diversion Ditch around Great Western Reservoir and into Big Dry Creek. The Walnut Creek tributaries, from north to south, are described below:

<u>McKay Ditch</u> - The headgates for this ditch are located at Coal Creek, approximately three miles west of the IA. Flow is typically present only during spring runoff and during City of Broomfield water transfers to Great Western Reservoir. McKay Ditch does not receive runoff from the IA and analytical data from this drainage are not discussed in this report.

<u>No-Name Gulch</u> - This drainage is located downstream from the RFETS sanitary landfill. Runoff from the IA does not flow into this basin; analytical data from this area are not discussed in this report.

<u>North Walnut Creek</u> - Runoff from the northern portion of the IA flows into this drainage, which has four detention ponds (Ponds A-1, A-2, A-3, and A-4). Ponds A-1 and A-2 are kept off-line and maintained for emergency spill control; water levels in these ponds are controlled by evaporation or transfer. Pond A-1 also receives water pumped from the Landfill Pond roughly once per year. North Walnut Creek flow is diverted around Ponds A-1 and A-2 to Pond A-3, where water is held and settling of solids occurs. Pond A-3 is transferred in batches to the A-series "terminal pond," Pond A-4, which also receives water transferred from Pond B-5. Once filled to a predesignated level, Pond A-4 water is isolated, sampled and

released if water quality standards are met. These offsite discharges, each averaging approximately 14 million gallons (43 acre-feet), typically occur 8 to 10 times per year.

The average annual discharge to North Walnut Creek is approximately 119 acre-feet (39 million gallons). The average mean daily flow rate in North Walnut Creek (at station SW093), from October 1992 through April 1997, was 0.16 cubic feet per second (cfs) and the maximum mean daily flow rate during this period was approximately 9 cfs. The combined capacity of the North Walnut Creek detention ponds (A-series ponds) is approximately 52 million gallons (160 acre-feet).

South Walnut Creek - Runoff from the central portion of the IA flows into this drainage, which has five detention ponds (Ponds B-1, B-2, B-3, B-4, and B-5). Ponds B-1 and B-2 are kept off-line and maintained for emergency spill control; water levels in these ponds are controlled by evaporation or transfer. Pond B-3 receives effluent from the RFETS Waste Water Treatment Plant (WWTP) and flows into Pond B-4. South Walnut Creek flow is diverted around Ponds B-1, B-2, and B-3, into Pond B-4, which flows continuously into terminal pond Pond B-5. After filling to a predesignated level, Pond B-5 is pump transferred in batches of approximately 9 million gallons to Pond A-4 (8 to 10 times per year), which is discharged offsite as described above.

The average annual discharge to South Walnut Creek, including effluent from the site WWTP, is approximately 258 acre-feet (84 million gallons). The average mean daily flow rate measured in South Walnut Creek (at station GS10), from October 1992 through April 1997, was 0.12 cfs and the maximum mean daily flow rate during this period was approximately 5 cfs. The combined capacity of the South Walnut Creek detention ponds (B-series ponds) is approximately 27 million gallons (83 acre-feet).

2.4.3 Woman Creek / South Interceptor Ditch (SID)

South of the IA is the Woman Creek / South Interceptor Ditch (SID) system. Descriptions of these drainages are provided below:

SID - Surface water runoff from the southern portion of the IA is captured by the SID, which flows from west to east into Pond C-2. After 1983, Pond C-2 was pump discharged to the Broomfield Diversion Ditch after reaching a predesignated level. Water from Pond C-2 is now sampled and, if surface water quality standards are met, pump discharged into Woman Creek which flows east off the site to the Woman Creek Reservoir. These offsite discharges, averaging approximately 11 million gallons (33 acre-feet), typically occur once per year during the winter.

There is frequently no flow in the SID. The average mean daily flow rate (at station SW027), from October 1994 through April 1997, including the periods of no flow, was 0.05 cfs and the maximum mean daily flow rate during this period was approximately 6 cfs.

Woman Creek - South of the SID is Woman Creek, which flows through Pond C-1 and offsite at Indiana Street. The Woman Creek drainage basin extends eastward from the base of the foothills, near Coal Creek Canyon, to Standley Lake. Woman Creek currently flows into the Woman Creek Reservoir, where it is held for eventual pumping to the Broomfield Diversion Ditch. The average annual yield of the basin is approximately 341 acre-feet (111 million gallons). The average mean daily flow rate in Woman Creek (at Indiana Street), is 0.47 cfs and the maximum mean daily flow rate during this period was approximately 76 cfs.

2.4.4 Other Drainages

The D-series Ponds (D-1 and D-2) are located on the Smart Ditch, located south of Woman Creek. Smart Ditch is hydrogeologically isolated from the RFETS IA, however, Smart Ditch does collect surface water runoff from surface soils with low levels of wind-blown radionuclide contamination. This drainage and these ponds are not discussed in this report.

2.5 ACTINIDE SOURCE AREAS AT RFETS

This section presents a summary of actinide source areas at RFETS, including the 903 Pad and Lip Area, the Sludge Dispersal Area, Solar Ponds and the Old Landfill and Ash Pits. Data contained in the Historical Release Report (DOE, 1992 and yearly updates) was used to compile the following summary of actinide source areas at RFETS. A summary of sampling events used to identify potential source areas is listed in Appendix C.

<u>Plutonium and Americium in the 903 Pad Area</u>

The main source of plutonium and americium in the environment at RFETS is the former drum storage area known as the 903 Pad with lesser contributions from the 1957 and 1969 fires (Meyer et al., 1996). The majority of plutonium and americium is associated with surface soils (0 to 6 inches {0 to 15 cm}). The distribution of plutonium and americium in surface soils is shown in Figures 4-1 and 4-2. The plutonium and americium contamination of the 903 Pad and Lip Area and the soils to the east and southeast of the 903 Pad, extending to east of Indiana Street, were generated during a combination of high wind events and earth moving activities in the period from 1967 through 1969. Inventory removal of the 903 Drum Storage Area began in January of 1967 and continued until mid-1968. The asphalt pad was placed on the former drum storage area in November 1969.

The Rocky Flats Plant 903 Area Characterization Final Report (Meyer et al., 1996) evaluated and summarized the history of the 903 Pad and Lip Area and correlated air monitoring results with wind events and physical disturbances of the 903 Pad soils. They concluded that "the significant airborne plutonium releases from the 903 Pad Area appear to be associated with a relatively few events, most likely high winds following mechanical disturbances" (Meyer et al., 1996). Covering the 903 Pad with fill and asphalt did not completely eliminate airborne contamination, although air concentrations were greatly reduced. Areas of soil outside of the pad were contaminated to a lesser extent than the primary 903 area, but remained subject to wind erosion. This "secondary resuspension" has been a significant relative source of offsite air contamination since 1970, and is discussed in some detail in Rope, et al. (1997). The hottest areas were removed through several projects in the 1970s.

Plutonium in surface soil has shown little redistribution over the years since the initial contamination in 1968-1969, but evidence has not ruled out that some local redistribution has re-occurred. Webb et al. (1996) demonstrated that plutonium concentrations and total deposition (from RFETS) decrease rapidly with distance from the 903 Pad and with deviation in direction from due east of the 903 Pad (Rope et al., 1997).

<u>Sludge Dispersal Area</u>

IHSS 141, the "sludge dispersal area" is located just west of the original east perimeter road, and consists of the former sewage sludge drying beds and related surface soil contamination. The beds were not lined, and excess liquid from the sludge could come in direct contact with the underlying soil.

Many times in the 40-year operation of sludge beds, sludge overflowed the beds and traveled overland down toward South Walnut Creek. Wind dispersion of plutonium-contaminated sludge also occurred, predominantly to the east of the beds. Walls and roofs were installed on the drying beds in 1994 reducing the potential for dispersal. Neither of these mechanisms is expected to contribute much plutonium to the environment. The potential for contamination of the soil and groundwater beneath the beds was considered high (DOE, 1992), prior to two studies confirming minimal impact (EG&G, 1991).

During the Operable Unit (OU) 6 investigation, activities of americium and plutonium were frequently detected above background screening levels at both IHSS 141 and 165, "the Triangle Area" (EG&G, 1996). This area was used to store drums containing plutonium residues, dilute nitric acid (few drums), and fire waste from the May 1969 plutonium fire. The contents of the drums were recoverable plutonium-bearing wastes and residues (DOE, 1992). Plutonium contamination of the surface soil at IHSS 165 occurred many times, each time, the affected soil was usually removed, or at a minimum, covered with gravel; the whole area was covered with gravel several times. The area was significantly disturbed in 1981 when the Perimeter Security Zone was constructed. The IHSS 165 area was cut to accommodate the fence.

Solar Ponds

Uranium was handled at RFETS beginning in 1952. Liquids containing plutonium solutions, uranium nitrate and other salts of plutonium and uranium from processing were pumped to the Solar Ponds beginning in 1953 and continuing until 1986. Increasing levels of uranium and nitrate in groundwater around the Solar Ponds were noted in seeps at the pond edge in 1954. By 1970, nitrate contamination was noted in North Walnut Creek downgradient of the Solar Ponds. A number of small trenches were installed in the 1970s to mitigate the contamination seeping from the ponds. An interceptor trench system (ITS) keyed into bedrock (in most areas) was installed in 1981 to collect groundwater downgradient from the Solar Ponds. All evaporation sludges were removed from the Solar

Ponds in 1986 through 1995. The ponds are now empty except for occasional rainfall capture.

Original Landfill and Ash Pits

The Original Landfill was used to dispose of plant non-combustibles from 1951 to 1968. Depleted uranium was disposed of occasionally and turnings are occasionally found on the ground surface (Jerry Anderson, personal communication, 1997). Uranium contaminated ashes from the plant security incinerator (destruction of classified paper) were also disposed of in the Original Landfill.

The Ash Pits located west of the Original Landfill were used to dispose of ashes from the plant incinerator. Prior to August 1968, all non-contaminated, non-classified combustible waste were sent to the incinerator. Because of the relatively low hazard from low levels of contamination with depleted uranium, dry combustibles (Kim-wipes, clothing, etc.) were considered non-contaminated and were incinerated; conversely, uranium was oxidized in the chip roaster, not in the incinerator, and the waste was disposed of offsite.

Trench T-1

Approximately 125 drums of depleted uranium machine turnings were disposed in Trench 1 (T-1) from 1954 until 1962. The trench was covered with 2 feet of soil as the drums were placed. There is no evidence that T-1 is a source of surface soil (wind blown) or groundwater uranium contamination (RMRS, 1997). Lesser amounts of depleted uranium were likely disposed in other trenches on the east side of the plant, however, there is no evidence that these trenches are a source of wind-blown or groundwater uranium contamination.

East Trenches

There are 10 waste burial trenches located outside the inner east gate that were used sequentially between 1954 and 1968. The primary waste stream was plutonium and uranium-contaminated sanitary sewage sludge. Other miscellaneous plutonium and uranium waste was also disposed of. Each trench remained open for approximately 1 to 2 years. While each was open, the potential existed for wind-borne resuspension; however, the likelihood of contaminant spread was low because the waste was below grade. Now that the trenches are covered and usually above the groundwater table, contaminant migration potential is low.

2.6 PREVIOUS ACTINIDE MIGRATION STUDIES AT RFETS

A number of actinide migration studies have been conducted at RFETS. These studies are summarized below and discussed further in the document as they pertain to a particular environmental media.

- Colorado Department of Public Health and Environment, 1994. *The Rocky Flats Dose Reconstruction Project, Phase II Toxicity Assessment and Risk Characterization*, Radiological Assessments Corporation.
- Hayden et al. 1975 *Particle Size Distribution of Plutonium on Soil Surface in Rocky Flats East Buffer Zone.* Rockwell International, Compiled September 26, 1975. This study analyzed the spatial distribution of plutonium particles in RFETS soil.
- Krey, P.W. and E.P. Hardy. 1970. *Plutonium in Soil Around the Rocky Flats Plant.* HASL-235. Soil samples were collected to a depth of 20 cm at 33 sites extending as far as 40 miles from RFETS and deposition concentrations of Pu-239 were plotted.

- Krey, P.W. and E.P. Hardy. 1972. *Plutonium Isotopic Ratios at Rocky Flats.* HASL-249. Mass spectroscopic analysis of plutonium recovered from soil samples around RFETS was used to update plutonium inventories around RFETS.
- Litaor, M.I. Litaor's work is compiled in Volume 13 of the *Phase II RFI/RI Report 903 Pad, Mound, and East Trenches Area,* October, 1995 and in the *Final RFI/RI Report OU3 (Offsite Areas)*, June 1996. The spatial and vertical distribution of PU-239/240, Am 2-41 and uranium isotopes was investigated to assess the nature and extent of plutonium, americium and uranium in the soils of the RFETS Buffer Zone and in offsite areas. This work included collection of 118 surficial samples; excavation and sampling of 26 soil pits in various distances and directions from a contaminated site; installation of a soil water monitoring system in five pits east of the 903 Pad; solid phase associations (speciation) using sequential extraction techniques; and rainfall simulation experiments.
- Little, C.A. and F.W. Whicker. 1978. *Plutonium Distribution in Rocky Flats Soil.* Health Physics 34:451-457. This report examines the patterns of plutonium contamination in RFETS soil and describes data on plutonium concentrations in soil, the relationship of concentration to location, depth and soil particle size and the likely contamination mechanisms.
- Little, C.A., F.W. Whicker, and T.F. Winsor. 1980. *Plutonium in a Grassland Ecosystem at Rocky Flats.* Journal Environmental Quality 9:350-353. This report discusses how plutonium particles entrapped in the fine fraction of surface soils were redeposited by wind transport.
- McDowell, L.M. and G.W. Whicker, 1978. *Size Characteristics of Plutonium Particles in Rocky Flats Soil.* Health Physics, 35:293-299. Soil was collected near the 903 Pad and a large plutonium oxide particle was isolated and studied.
- Poet, S.S. and E.A Martell, 1972. *Plutonium-239 and Americium-241 Contamination in the Denver Area*. Health Physics 23;537-548. PU-239 was measured in soils, surface water and sediments in offsite areas surrounding RFETS to assess contaminant distribution.

- Seed et al. 1971. *Committee Evaluation of Pu Levels in Soils Within and Surrounding USAEC Installation at Rocky Flats, Colorado*, Dow Chemical Company, RFP-INV-1. This report assesses the long-term potential hazard of plutonium contaminated soil under and around the 903 Pad.
- Webb et al. 1993. *A Study of Plutonium in Soil and Vegetation at the Rocky Flats Plant,* p. 611-623. In Kathren et al. (eds) Environmental Health Physics Proceedings, January 24-28, 1993. Coeur d'Alene, Idaho. The spatial distribution of plutonium was measured in the environment east of RFETS. The study area was centered on the primary plume of plutonium contamination in the area, which mostly originated from the 903 Pad.

2.7 REFERENCES

Anderson, Jerry, Rocky Mountain Remediation Services, personal communication, 1997.

DOE, 1992, Historical Release Report for the Rocky Flats Plant, June, 1992.

EG&G, 1991, Zero Offsite Water Discharge Study.

EG&G, 1995a, Groundwater Geochemistry Report for the Rocky Flats Environmental Technology Site: Sitewide Geoscience Characterization Study, Volume III, January, 1995.

EG&G, 1995b, Geologic Characterization Report for the Rocky Flats Environmental Technology Site: Sitewide Geoscience Characterization Study, Volume I, March, 1995.

EG&G, 1995c, Hydrogeologic Characterization Report for the Rocky Flats Environmental Technology Site: Sitewide Geoscience Characterization Study, Volume II, April, 1995.

EG&G, 1996, Final Phase I RFI/RI Report Walnut Creek Priority Drainage, Operable Unit 6, RF/ER-95-0119.UN, Rev 0, February, 1996.

Fedors, R., and J.W. Warner, 1993, Characterization of Physical and Hydraulic Properties of Surficial Materials and Groundwater/Surface water Interaction Study at Rocky Flats Plant, Golden, Colorado, Colorado State University, Fort Collins, CO.

Kaiser-Hill, 1995, 1994 Rocky Flats Environmental Technology Site Environmental Report.

Meyer, H. R., Rope, S.K., Winsor, T., F., Voilleque, P. G., Meyer, K.R., Stetar, L. A., Till, J. E., Weber, J. M., 1996, Rocky Flats Dose Reconstruction Project Phase II, Toxicity Assessment and Risk Characterization, Task 2, The Rocky Flats Plant 903 Area Characterization Final Report, RAC Report #2-CDPHE-RFP-1996-Final, December, 1996.

RMRS, 1996, White Paper - Analysis of Vertical Contaminant Migration Potential, Final Report dated August 16, 1996, prepared for Kaiser-Hill Company and the U.S. DOE.

RMRS, 1997, Draft Proposed Action Memorandum for the Source Removal at Trench 1, IHSS 108, April 25, 1997, Public comment draft. 35pp.

Rope, S.K., Meyer, K. R., Case, M. J., Schmidt, D. W., Winsor, T. F., Dreicer, M., Till, J. E., 1997, Rocky Flats Dose Reconstruction Project Phase II, Toxicity Assessment and Risk Characterization, Task 4, Evaluation of Historical Environmental Data Final Report, RAC Report #1-CDPHE-RFP-1997-Final, March, 1997.

3.0 THE GEOCHEMISTRY OF URANIUM, PLUTONIUM, AND AMERICIUM

This section reviews specific chemical reactions which determine the behavior of actinides in the environment and discusses their origin, occurrence, and behavior at RFETS.

Actinides are transition elements with partially filled 5f electronic orbitals. The 5f orbitals are screened from the chemical environment by higher lying s and p electrons, and this screening produces strong similarities among the chemical properties of elements in the group. The variation in chemical properties within the series is systematic and predictable, and some properties of the heavier members of the series were predicted prior to discovery (Seaborg and Loveland, 1990).

Chemical reactions which determine the behavior of actinides in the environment include reduction/oxidation, precipitation and coprecipitation, formation of aqueous complexes, sorption, and formation of finely divided particles (true colloids and pseudocolloids) (Allard and Rydberg, 1983; Choppin, 1988; Dozol and Hagemann, 1993; and Silva and Nitsche, 1995). The major salient points related to the actinides of concern at RFETS (uranium, plutonium, and americium) will be discussed below.

3.0.1 Reduction/Oxidation

A chemical reaction involving the loss of electrons is known as an oxidation reaction while any reaction involving gain of electrons is known as a reduction reaction. Oxidizing agents are materials that are reduced while taking on electrons driving oxidation reactions. Reducing agents are materials that are oxidized while donating electrons to drive reduction reactions.

Reduction and oxidation (redox) conditions strongly influence the environmental behavior of actinides. The actinides assume a number of valences (Table 3-1), but redox conditions in natural systems are commonly buffered by reactions involving major constituents such as the degradation of water, reduction/oxidization of iron, or reduction of naturally occurring organic matter.

Under common environmental conditions americium tends to occur primarily as Am(3), but uranium partition among valences of 4 and 6, and plutonium between valences of 3, 4, 5, and 6 (Allard et al., 1983). The single major valence of americium simplifies the study of its environmental behavior, but the more complicated behavior of plutonium and uranium commonly drives researchers to extrapolate behavior from single valent actinides and lanthanium group elements (lanthanides).

Table 3-1. Actinide Elements and Their Oxidation States

At..Wt..	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103
Element	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr
													1?		
							(2)	(2)		(2)	(2)	2	2	**2**	
	3	(3)	(3)	3	3	3	**3**	**3**	**3**	**3**	**3**	**3**	**3**	3	**3**
		4	4	4	4	**4**	4	4	4	4	(4)	4?			
			5	5	**5**	5	5	5?		5?					
				6	6	6	6	6?							
					7	(7)	7?								

From Katz et al. (1986); Bold & underline valences are the most stable oxidation states; Bracketed valences are unstable.

Actinides (generically designated M) in the 3, 4, 5, and 6 valences form M^{+3}, M^{+4}, MO_2^{+}, and MO_2^{2+} cations respectively (Cleveland, 1979). The simple cations (M^{+3} and M^{+4}) inter-convert rapidly, and the oxygenated actinyl ions (MO_2^{+} and MO_2^{2+}) inter-convert rapidly, but conversions between simple and oxygenated cations are relatively slow because they require extensive changes to the linear dioxo structure before electron transfer can occur (Cleveland, 1979; Choppin, 1983).

This slow conversion can produce significant disequilibria in systems involving both types of cations. Experiments in ponds at Oak Ridge, for example, showed that dissolved Pu(V) could be reduced to Pu (III+IV) by adding glucose to force the water anaerobic, but when the system was reaerated Pu(V) returned to solution slowly, and at three months Pu(V) remained at less than one fifth of the initial value (Watters, 1983).

Laboratory oxidizing and reducing agents also affect the redox state of actinides, and experiments which use redox reagents to destroy major soil phases to establish the location of the actinides must take these effects into account. Both Bunzl et al. (1995) and Litaor and Ibrahim (1997), attempted to establish the relationship between plutonium and major soil phases using strong reducing and oxidizing agents to destroy sesquioxides and organic carbon respectively, but did not consider the effects of these agents on the redox state of plutonium itself. This oversight renders their conclusions that organic matter and iron sesquioxides are largely responsible for the affinity of soils for actinides a yet unproved hypothesis (Marty et al., 1997a). Their conclusions contradict earlier work showing little effect on the affinity of soils for actinides from the removal of organic matter and sesquioxides (Bondietti and Tamura 1980)(except for the pentavalent valence; Table 3-2).

Table 3-2. Effect of Clay Treatment on Adsorption of Actinide Elements to Miami Silt Loam Clay

Treatment	CEC	Percent adsorbed			
	meq/100 g	Th-234 (IV)	Cm-244 (III)	U-234 (IV)	Np-237 (V)
Intact soil	17	99.7	98.9	95.6	61.8
Organic matter removed	11	99.8	99.6	96.4	49.7
Fe and organic matter removed	9.9	99.7	95.6	99.1	18.2

From Bondietti and Tamura (1980)

3.0.2 Coprecipitation and Precipitation

Actinides entered the RFETS environment primarily as reactive metals or in solution rather than as slow reacting thermodynamically stable or metastable phases. The behavior of the RFETS actinides, therefore, contrast in many respects with that of actinides deposited following thermonuclear explosions (high-fired actinides), deposited following explosions of high explosives (low-fired actinides), or deposited in the form of refractory wastes resistant to nitric, hydrofluoric, and hydrochloric acid digestion. Actinides found in RFETS soils are not undergoing rapid recrystallization, and their speciation and associations in the soils of RFETS have not been conclusively determined (Marty et al., 1997a).

Actinide hydroxide/oxide have been observed to form discrete particles (precipitates) in some areas of RFETS, but the observed abundances are not sufficient to account for the entire plutonium inventory (McDowell and Whicker, 1978). Actinide hydroxides and oxides precipitate from solution through a well characterized process which involves hydrolysis of actinide ions in solution (Cleveland, 1979). The hydrolyzed actinides then form polymers of various lengths (Cleveland, 1979; Clark, 1994). The extent of polymerization depends on the concentration of actinides in solution, and the reaction may not be easily reversible. Polymerization of plutonium, for example, forms networks of $Pu(OH)_4$ linkages, but as the polymers age oxygen bridges increase in abundance, and the material begins to resist dissolution even in concentrated nitric acid (Toth et al., 1983; Choppin, 1983). This resistance may render simple solubility constants (K_{sp}) calculated for solid actinide hydroxides invalid (Choppin, 1983) and can affect apparent distribution coefficients (K_d) for systems containing actinide hydroxides.

$$[Pu(OH)_x]^{4-x} + [Pu(OH)_x]^{4-x} \leftrightarrow \left[(HO)_{x-1}\begin{matrix} & OH & \\ Pu & & Pu \\ & OH & \end{matrix}(HO)_{x-1}\right]^{2(4-x)} \quad \text{(Toth et al., 1983)}$$

Upon aging the hydroxyl bridges convert to oxo-bridges:

$$\begin{matrix} & OH & \\ Pu & & Pu^{n+} \\ & OH & \end{matrix} \rightarrow \text{--Pu--O--Pu--}^{n+} + H_2O$$

3.0.3 Sorption

Sorption on geological materials is an important control on the environmental behavior of actinides, and sorption reactions are one of the chief causes for the limited mobility of most actinides in the environment. After 30 years of radioactive releases from the waste-water treatment facility at Los Alamos, for example, plutonium moved less than 3 meters (m) into the tuff (Stoker et al., 1991) and at RFETS plutonium activity in the Area is largely in the top 25 cm of the soil profile (Section 4). Physical adsorption, chemisorption, and electrostatic adsorption all appear to affect the environmental behavior of actinides (Benes and Majer, 1980; Allard and Rydberg, 1983), but prediction of sorption behavior remains a major weakness in determining the environmental behavior of actinides. Sorption studies remain empirical, and the K_ds are only valid under very limited conditions (Dozol and Hagemann, 1993).

One problem is the partially irreversible nature of sorption/desorption reactions. Some of this behavior may be due to artifacts, but experiments on the sorption of plutonium by red clay show that sorption/desorption reactions remain irreversible even after possible artifacts are accounted for (Higgo and Rees, 1986).

3.0.3.1 Physical Adsorption

Physical adsorption occurs by "non-specific" forces which attract solute to sorbent and binds solute species in consecutive layers to the exposed solid surface. This mechanism is rapid, non-selective, reversible, fairly independent of concentration in solution, and only slightly dependent on ion exchange capacity.

3.0.3.2 Chemisorption (or Specific Adsorption)

Chemisorption (or specific adsorption) results from specific chemical forces between sorbent and solute. This process can be regarded as complex formation and is commonly specific and selective, concentration dependent, and may be slow and only partially reversible.

Figure 3-1 shows typical sorption behavior for actinide ions on oxide surfaces. Actinides and other transition metals typically exhibit a sharp "sorption shoulder" which coincides with formation of the first hydrolysis complex in solution (Farley et al., 1985). Hydrolysis complexes of the form $M(OH)^{n-1+}$ appear responsible for the shoulders. These complexes are less charged than the parent (M^{n+}) ions, and the sharp increase in sorption associated with their formation shows that the interaction is "non-coulombic" and does not involve simple electrostatic attraction which would be greater for the more highly charged uncomplexed actinides (it is "non-coloumbic") (Stumm and Morgan, 1981).

There is a considerable body of evidence suggesting that specific sorption is important with actinides. At Los Alamos, for example, plutonium was strongly held by a variety of materials including tuff which has an ion exchange capacity of only 0.5 to 3 miliequavalents/ 100 g (Christenson et al., 1958). Organic matter-free soils from Hanford showed similar behavior, and a large percentage of plutonium was adsorbed by soil almost immediately (Rhodes, 1957).

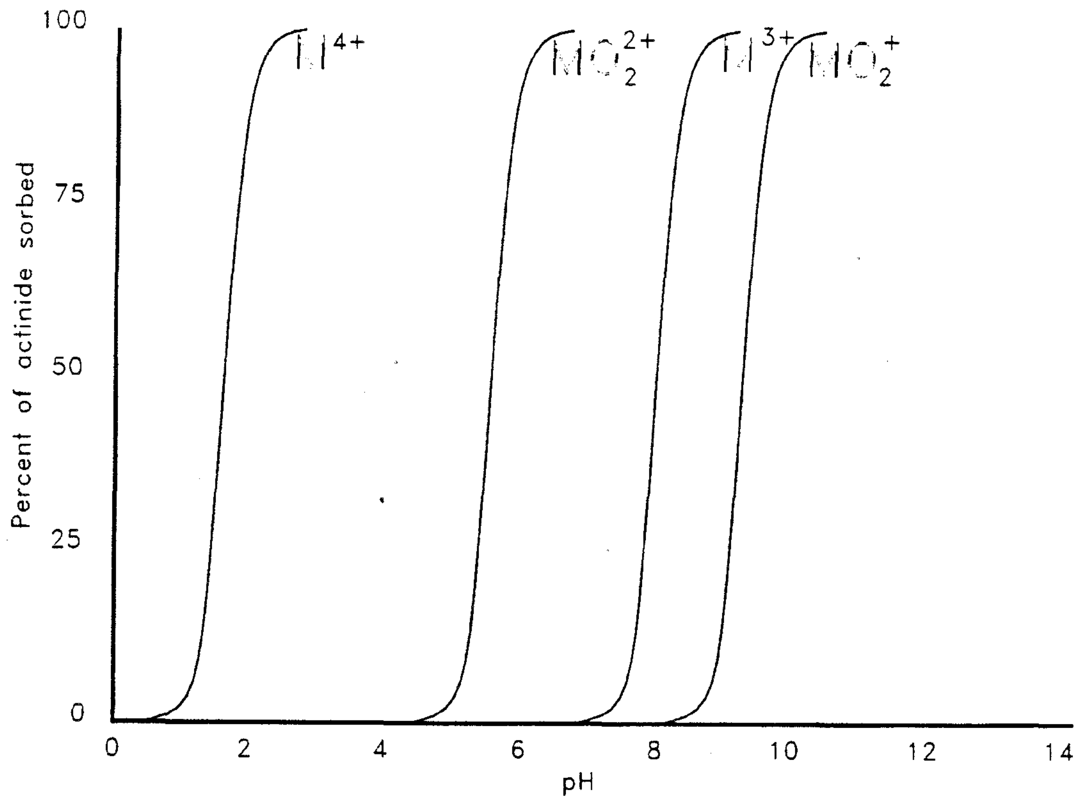


Figure 3-1. Typical Curves for Specific Sorption of Actinides on Solid Oxides

The mechanism of specific adsorption has not been totally elucidated but appears to have much in common with that of hydroxide precipitation.

3.0.3.3 Electrostatic Adsorption/Ion Exchange

Electrostatic adsorption/ion exchange is a common interaction between solid and species in solution and is due to coulomb forces which attract species from solution to solid surfaces. The process is dependent upon concentration.

Electrostatic adsorption also affects the behavior of actinides in the environment. Actinides which entered the environment as solutions or metals tend to be concentrated in the fine fraction of soil and sediments which also has the highest cation exchange capacity (Kingsley, 1947; Hakonson and Nyhan, 1980; Purtymun et al., 1983; Watters et al., 1983; and Little and Whicker, 1978). In Mortandad Canyon at Los Alamos, for example, plutonium concentrations in the silt and clay fraction are seven times the concentration in the coarser fractions of alluvium (Dahlman et al., 1980; and Hakonson and Nyhan, 1980).

A number of studies, including recent work by Litaor and Ibrahim (1997), have shown that a small fraction of the plutonium can be removed from soil with simple salt solutions. A small fraction of actinides is held in the exchange sites under normal conditions; but the fraction held by electrostatic sorption will increase if plutonium becomes less strongly held by specific sorption. It has been suggested, for example, that reduction of soils under natural conditions could destroy iron oxides and decrease specific sorption of actinides. Under such conditions, ion exchange reactions should increase in importance.

Electrostatic adsorption onto soils and sediments depends on the charge of the stationary phase, and this charge changes with solution pH. Soil particles are positively charged at low pHs, but shift to a negative charge at higher pH values. The pH at which the particles have no net-charge is known as the zero point of charge (Table 3-3). The positively charged surfaces formed at low pH will retard movement of anions, and the negatively charged surfaces formed at high pH will retard movement of cations (Stumm and Morgan, 1981). Under environmental conditions most surfaces in soil will be negatively charged and attract cations, and even positively charged minerals tend to be coated with natural organic matter (NOM) which provides a negative charge irrespective of the original surface.

Ions in solution follow a general order of affinity during ion exchange reactions. This affinity is caused by coulombic interactions among counter ions and the exchanger, and ion-dipole and

Table 3-3. Zero Point of Charge for Soil Constituents of Possible Significance at RFETS

Material	pH_{zpc}
α-Al_2O_3	9.1
α-$Al(OH)_3$	5.0
γ-AlOOH	8.2
Fe_3O_4	6.5
α-FeOOH	7.8
γ-Fe_2O_3	6.7
"$Fe(OH)_3$"(amorph)	8.5
δ-MnO_2	2.8
β-MnO_2	7.2
SiO_2	2.0
feldspars	2-2.4
kaolinite	4.6
montmorillonite	2.5

From: Stumm and Morgan (1981)

induce dipole interactions (Eisenmann, 1962). Normally the first factor is weak compared to the second and the affinity sequence follows the Hofmeister series where ions of small hydrated radius are preferred over ions of large hydrated radius (Stumm and Morgan, 1981):

$Cs^+ > K^+ > Na^+ > Li^+$
$Ba^{2+} > Sr^{2+} > Ca^{2+} > Mg^{2+}$
$Pu^{3+} > Am^{3+}$
$U^{4+} > Pu^{4+}$

Ions of smaller hydrated radius (such as Pu^{3+}) displace those of higher radius (such as Am^{3+}) and high charge ions (such as Pu^{3+}) are preferred over low charge ions (such as Ca^{2+} and Na^+).

3.0.4 Aqueous Complexes

Actinides form strong complexes with a range of inorganic anions, organic compounds with negatively charged functional groups, and synthetic complexing agents. These reactions influence the solubility of actinides in solution and greatly increase the apparent redox stability of valences which form the strongest complexes (Choppin, 1983). Figure 3-3 shows the effects of complexing agents on sorption reactions. In general, formation of actinide-anion complexes reduces the quantities of free ions available for hydrolysis and shifts both sorption and precipitation curves to higher pHs.

The strength of complexes with inorganic anions follows the order:

$M^{4+} > M^{3+} > MO_2^{2+} > MO_2^{1+}$

$F^- > NO_3^- > Cl^- > ClO_4^-$

$CO_3^{2-} > SO_3^{2-} > C_2O_4^{2-} > SO_4^{2-}$

The thermodynamic constants for these actinide complexes are being critically reviewed and compiled as part of a European Nuclear Energy Agency (NEA) initiative (Dozol and Hagemann, 1993). Data for uranium currently are available, but data for plutonium and americium are not complete. Plutonium is the most complicated system among the actinides because of the large number of possible valences involved, and Table 3-4 provides a compilation of stability constants for important complexation reactions in this system.

Table 3-4. Complexes of Trivalent and Tetravalent Plutonium

	Reaction	Equilibrium Constant	Constant
EDTA	$Pu^{4+} + H_2Y^{2-} \Leftrightarrow 2H^+ + PuY$	$[PuY][H^+]^2/[Pu^{4+}][H_2Y^{2-}]$	=4.57x10*
Citrate	$Pu^{4+} + C_6H_5O_7^{3-} \Leftrightarrow Pu(C_6H_5O_7)^{1+}$	$[Pu(C_6H_5O_7)^{1+}]/[Pu^{4+}][C_6H_5O_7^{3-}]$	$=3.0\times10^{15}$
Citrate	$Pu(C_6H_5O_7)^{1+} + C_6H_5O_7^{3-} \Leftrightarrow Pu(C_6H_5O_7)_2^{2-}$	$[Pu(C_6H_5O_7)_2^{2-}]/[Pu(C_6H_5O_7)^{1+}][C_6H_5O_7^{3-}]$	$=1\times10^{30}$
EDTA	$Pu^{3+} + H_2Y^{2-} \Leftrightarrow 2H^+ + PuY^-$	$[PuY^-][H^+]^2/[Pu^{4+}][H_2Y^{2-}]$	$=1.3\times10^{18}$
Citrate	$Pu^{3+} + C_6H_5O_7^{3-} \Leftrightarrow Pu(C_6H_5O_7)^0$	$[Pu(C_6H_5O_7)^0]/[Pu^{3+}][C_6H_5O_7^{3-}]$	$=7.3\times10^{8}$

* Cleveland (1979)

3.0.5 Pseudo-Colloids and True Colloids

McCarthy and Zachara claimed that small negatively charged particles move in solution under special conditions, and that these complexes can transport actinides quickly through groundwater across large distances (McCarthy and Zachara, 1989). Actinides complexed with high molecular weight organic molecules, sorbed on clays, sorbed on hydrated iron oxides and hydrated aluminum oxides (*"psuedo-colloids"*), and actinides trapped within finely divided actinide hydroxides and oxides (*"true colloids"*) have been suggested as mobile phases (Puls and Powell, 1992; Robertson, 1984; Ryan and Gschwend, 1990; Nightengale and Bianchi, 1977; and Kim et al., 1984).

The chief example of the potential significance of such colloids in transporting radionuclides has been the appearance of plutonium in monitoring wells 3 km from the source of contamination in Mortandad Canyon at the Los Alamos National Laboratory (McCarthy and Zachara, 1989; and Penrose et al., 1990). Recently, however, it has been demonstrated that plutonium moved down this canyon in surface runoff and not through groundwater (Marty et al., 1997b).

Such transport of actinides on colloids has been hypothesized to be active at RFETS (Harnish et al., 1994; and Harnish et al., 1996). The results of these studies, however, are inconclusive because the data on which interpretations were based are less than detection limits and adequate safeguards may not have been in place to prevent actinide contamination of the monitoring equipment when it was installed through contaminated surface soil.

Theoretical work on extremely fine particles in water, moreover, suggests that colloids should be effectively screened from groundwater over short distances through the action of natural collectors (Yao et al., 1971). Natural analogs cast further doubt on the significance of this mechanism. Natural Th^{4+}, for example, forms strong complexes with natural organic matter but remains largely immobile in soils presumably as a result of competing reactions.

Facilitated transport of plutonium complexed by synthetic complexing agents, however, has been unequivocally demonstrated for ethylene diamine tetra acetic acid (EDTA)-plutonium complexes at the MaxiFlats disposal site (Cleveland and Rees, 1981), and NOM and other colloidal materials form aqueous phase complexes with actinides and stabilize plutonium in lake water (Nash and Choppin, 1980; Watters, 1983; and McCarthy and Zachara, 1989). Therefore, complexes of actinides with NOM and other colloids may increase the rate of actinide transport, although it has not been clearly demonstrated to date.

The general processes described above control the environmental behavior of actinides, but the chemical properties of uranium, plutonium, and americium also differ in many respects. Environmental conditions also vary from site to site influencing the behavior of actinides. The following sections contain a more detailed discussion of the effects of the specific chemistry of the individual actinides, specifically uranium, plutonium, and americium under the soil and groundwater conditions found at RFETS.

3.1 URANIUM

3.1.1 Origin and Occurrence of Uranium

Uranium (element 92) occurs naturally in the earth's crust with an average concentration of 2.7 mg/kg. Uranium is a lithophilic element which is most abundant in granites (averaging 5 mg/kg and shales (averaging 3.5 mg/kg; Krauskopf, 1979). Myrick et al. (1983) evaluated the concentrations of U-238 in surface soils across the United States to determine background levels. Surface soils of Colorado were found to range from 0.47 to 3.0 pCi/g with a mean and standard deviation of 1.2 pCi/g and 0.91 pCi/g, respectively.

Natural uranium is 99.273% U-238, but also contains small amounts of U-234 and U-235 (0.005 and 0.72%, respectively in most cases). The mass differences among the uranium isotopes is minor and the isotopes do not normally fractionate through natural physical or chemical processes (Faure, 1977). U-238 has a long half-life (4.51×10^9 years) and decays to Pb-206 through a chain which includes U-234 (Eisenbud, 1987). U-234 has a relatively short 248,000 year half-life but once secular equilibrium is established the radioactivity of U-234 exactly equals the radioactivity of U-238. U-235 decays through a separate chain to Pb-207 with a half-life of 7.13×10^8 years (Eisenbud, 1987).

3.1.2 Geochemistry of Uranium

Uranium assumes 4 and 6 valences in soil. As with all actinides, the 4 valence hydrolyzes, precipitates easily, undergoes strong specific sorption reactions, and is preferred over other cations in ion exchange reactions. These reactions render U(4) largely immobile in the environment despite highly stable complexes with inorganic and organic ligands. The more oxidized U(6) is more soluble, undergoes weaker specific sorption, and tends to be more mobile (Salomons and Foerstner, 1984).

Anions, such as carbonate, nitrate, chloride, fulvic acid, humic acid, and EDTA, form complexes with U(4) and U(6) and increase the amount of uranium which can remain in solution. This, in turn, increases the overall mobility of the uranium. Uranium, generally, is least mobile in reducing (anaerobic) environments free of complexing anions and most mobile in oxidizing (aerobic) environments with high concentrations of complexing anions.

Natural uranium is ubiquitous in the Front Range of Colorado and complicates studies of uranium at RFETS. High uranium granites occur throughout the front range, and uranium ore (the Schwartzwalder mine) is located near RFETS. The natural alkaline and oxidizing environment in near-subsurface water mobilize uranium in groundwater, and "...higher uranium concentrations in water samples...are probably due to leaching of uraniferous strata in the Pierre and Laramie formations..." The South Platte River is "...anomalously rich in uranium compared to most other rivers of its size." (Bolivar et al., 1978)
The isotopic abundances (by weight) in some of the uranium used at RFETS differed significantly from natural values, and this may be useful in determining which uranium represents RFETS contamination (Table 3-5). Both U-234 - U-235 enriched and U-234 - U-235 depleted nuclear-weapons components were manufactured at RFETS (EG&G, 1988), and the isotopic signatures of both types of contamination can be differentiated from natural

Table 3-5. Isotopic Ratios in Potential Sources of Uranium at RFETS

	Natural Uranium*	Depleted Uranium**	Enriched Uranium**
		Percent by Weight	
U-238	99.273%	99.75%	5%
U-235	0.72%	0.25%	95%
		Activity Ratio	
U-233/234	0.005	0.0005	TBD
U-234/U-238	1.06	0.09	>>5.74

- Naturally found in soils at RFETS; ** Contributed by industrial use of RFETS.
- TBD - to be determined

uranium. Unfortunately, most samples collected from RFETS have been analyzed by alpha-spectroscopy, and this technique provides only an estimation of U-235 activity.

Efurd et al. (1993) used thermal ionization mass spectrometry (TIMS) to measure U-234, -235, -236, and -238 in RFETS sediment and water samples. The technique is more accurate than alpha-spectroscopy and provides more certain isotopic ratios. On the basis of this data the authors concluded that the "...largest source of radioactivity in the terminal ponds was naturally occurring uranium and its decay product radium," and that the "...largest source of anthropogenic radioactivity in the terminal ponds was depleted uranium." Approximately half the uranium present in Ponds A-4 and C-2 and approximately 20% of the uranium present in Pond B-5 apparently originated as depleted uranium. These results are significant because they allow uranium contributed by industrial to be differentiated from uranium which occurs naturally.

U-236 is produced by neutron capture on U-235 in nuclear reactors or atomic explosions and does not occur in nature or in uranium which has not been through a reactor (Efurd et al., 1993). U-236, therefore, would not be expected in the uranium used at RFETS. Efurd et al. (1993), however, detected U-236 in some samples and concluded that the "...presence of U-236 in the surface-water samples collected at RFP (*RFETS*) and the variable U-238/U-235 atom ratios detected in water samples collected from the holding ponds prove that anthropogenic uranium is present." This probably represents uranium subject to neutron flux during an explosion and may be atmospheric fallout from atomic testing.
U-238/U-235 ratios for dissolved uranium in RFETS groundwater, from which non-detects have been excluded, show a wide scatter. This could be due to lack of a systematic treatment of sampling and analytical error or real variability in isotopic ratios. The most likely explanation is unpropagated error because background wells show high variability in isotopic ratios which cannot be otherwise explained. U-234/U-238 *activity* ratios can be used to distinguish between natural, enriched, and depleted uranium (Table 3-5).

The ratio should be 1.0 at secular equilibrium, but the ratios ranged from <1.0 to >2.5 for background areas (DOE, 1993a). If analytical errors were correctly handled in this study, this would indicate that unexpected factors affected U-234/U-238 activity ratios limiting its usefulness in distinguishing between natural and RFETS uranium.

DOE (1993a) reported a range of 1.19 to 2.43 for ratios of uranium isotopes in filtered background groundwater and stream water, and DOE (1995b) reported U-234/ U-238 ratios ranging from 0.34 to 18.5 for UHSU groundwater at the Solar Ponds. Neither report systematically dealt with analytical errors and the results, therefore, are of limited usefulness.

In summary, the results from most of the studies of isotopic ratios undertaken to date have not systematically dealt with error. Time Integrated Mass Spectroscopy (TIMS) analysis shows promise as a means to determine the source of uranium because its analytical errors are smaller and isotopic ratios can be determined more precisely. TIMS could allow natural uranium and anthropogenic uranium to be better determined. This may be important because background levels set natural limits on the effectiveness of cleanup, and the differentiation of scontaminated areas from uncontaminated areas could allow cleanup efforts to be focused.

3.2 PLUTONIUM

3.2.1 Origin and Occurrence of Plutonium

Plutonium was the second transuranic element discovered and the first transuranic element to be produced in macroscopic quantities (Seaborg, 1958). It has been produced in far greater quantities than any other transuranic element because of its usefulness in producing atomic weapons and power. The plutonium used at RFETS was weapons-grade and consisted primarily of Pu-239 (half-life of 2.44×10^4 years) with lesser amounts of Pu-238 (half-life of 87.74 years), Pu-240 (half-life of 6,580 years) and higher isotopes.

Plutonium does not occur in nature in significant amounts, but an anthropogenic background of Pu-239, Pu-240, and Pu-241 exists worldwide due to fallout from atmospheric nuclear-weapons tests. A considerable background of heat-source plutonium (Pu-238) also occurs due to the atmospheric burnup of a nuclear-powered satellite (SNAP-9A) over the Southern Hemisphere in 1964 (Hardy et al., 1973).

The distribution of fallout plutonium across the earth's surface is not uniform; geographic, orographic, and meteorologic effects produced spatial variations in fallout. Hardy et al. (1973) studied the distribution of fallout plutonium and measured the isotopic ratios in soil samples collected from around the world. They determined that the heaviest fallout of Pu-239 and Pu-240 lies in the temperate latitudes in the Northern Hemisphere, whereas, concentrations of Pu-238 are greatest in the temperate latitudes of the Southern Hemisphere (Hardy et al., 1973). Purtymun et al. (1990) studied the deposition and distribution of plutonium from worldwide fallout and concluded that the "...differences in plutonium concentrations and ratios...can be attributed to regional and local weather patterns and to distribution by physical transport..." and that "...variability in plutonium particle size also contributes to the inconstancy of plutonium concentrations and ratios found in soils and sediments."

The plutonium used at RFETS was exclusively "weapons-grade" and was primarily in a metallic form. This plutonium is predominantly Pu-239 (93.79% by weight) with small amounts of Pu-240 (5.8% by weight) and traces of Pu-238 (0.01 % by weight), Pu-241 (0.36% by weight), and Pu-242 (0.03% by weight). Some low pH plutonium-containing solutions also were used at the plant as part of processes to recover plutonium.

3.2.2 Geochemical Behavior of Plutonium

The usefulness of plutonium in producing atomic weapons and as a power source has resulted in extensive studies of the solution chemistry of plutonium, including the interaction of plutonium solutions and metals with soil (Seaborg and Loveland, 1990). The environmental chemistry of plutonium is complicated by the large number of reactions involved, but despite the relatively recent discovery of the element, its major reactions are well characterized (Seaborg and Loveland, 1990; Choppin, 1983).

As discussed above, the major reactions influencing the environmental fate of plutonium are reduction-oxidation (Eh controlled), formation of complexes with anions and NOM (controlled by pH and strength of complexing anions), precipitation (controlled by solution composition), and sorption (controlled by solution composition and the nature of solid phases). Formation and transport of colloids also may be a mechanism for the movement of plutonium (Essington and Fowler, 1976; Nevissi et al., 1976) even though the importance of this as a groundwater mechanism appears overstated. Harnish et al. (1994) attempted to examine plutonium colloids at RFETS, but used data which were less than detection limits to support their conclusions and did not consider the potential artifacts produced by emplacement of groundwater monitoring wells through plutonium-contaminated soil These problems also affected later work by these authors (Harnish et al. 1996).

A number of studies have suggested that plutonium is not absolutely chemically immobile in the environment under all conditions. Noshkin et al. (1976), for example, showed that, at the Enewetak Atoll, plutonium had migrated 80 m downward to groundwater. This environment contrasts with that of RFETS: the actinides were initially trapped in calcium oxides, hydroxides, and carbonates, the seawater is high in complexing anions, and the soils and sediments lack both silicate and metal sesquioxides to sorb plutonium. It, therefore, is not too surprising that the authors found Pu-239+240 to be "...very mobile throughout the water-saturated coral-sand environments" (Essington and Fowler, 1976).

Litaor and Ibrahim (1996) hypothesized that plutonium might be chemically mobilized under environmental conditions at RFETS, but the mechanism by which movement would occur was not well-defined. The Actinide Migration Studies will evaluate the data.

Rusin et al. (1994) demonstrated that iron-reducing bacteria in combination with strong artificial complexing agents "mediate the solubilization of hydrous $PuO_2(s)$ under anaerobic conditions." As much as 90% of PuO_2 was "biosolubilized" experimentally in 6 to 7 days. As will be discussed in subsequent sections, even relatively weak artificial complexing agents, such as citrate, can move PuO_2 into solution when used in conjunction with strong reducing agents such as dithionite. Strong artificial complexing agents, such as EDTA or the nitrilotriacetic acid (NTA) used by Rusin et al. (1994), can solubilize $PuO_2(s)$ under weakly reducing conditions such as those induced by iron reducing bacteria.

3.3 AMERICIUM

3.3.1 Origin and Geochemical Behavior of Americium

Americium at RFETS primarily forms as a result of the decay of Pu-241 (half-life = 14.4 years), and ingrows within weapons plutonium as the relatively short-lived Pu-241 decays. Americium was also purified by means of a molten salt extraction and sold for commercial applications. Americium oxide was sent as a product to Oak Ridge National Laboratories. As with plutonium, americium is not found in nature in significant quantities, but a world-wide background occurs as a result of bomb tests.

3.3.2 Geochemistry of Americium

Americium can exist in multiple oxidation states (III, IV, V, VI), but is expected to be in the III state in aerated waters in the absence of oxidants other than atmospheric oxygen. The geochemical behavior of americium in the environment is similar to that of plutonium; both actinides tend to be strongly adsorbed to the solid phase under neutral to alkaline, oxidizing conditions.

As discussed above, the major reactions influencing the environmental fate of americium are formation of complexes with anions and natural organic matter (controlled by pH, and strength of complexing anions), precipitation (controlled by solution composition), and sorption (controlled by solution composition and the nature of solid phases). Americium also may form psuedo and true colloids which could potentially migrate through groundwater although evidence of such migration is equivocal (Silva and Nitsche, 1995).

Am^{3+}should behave in much the same manner as Pu^{3}, and the behavior of Am^{3+}may help elucidate the environmental behavior of trivalent actinides. The distribution of $Am^{3+}$and Pu^{4+}at RFETS generally are similar. This suggests that differences in the environmental chemistry of $Am^{3+}$and Pu^{4+}may not significantly affect their environmental behavior over a period of decades, and that reduction of $Pu^{4+}$to Pu^{3+}under natural conditions may not quickly affect the distribution of plutonium.

3.4 DETERMINING PARTITION COEFFICIENTS FOR ACTINIDES

As stated above, sorption studies remain empirical, and distribution coefficients which are measured are only valid under the very limited conditions in which they were determined (Dozol and Hagemann, 1993).

Prediction of aqueous actinide transport in soils and groundwater is dependent on an understanding of contaminant mobility in the soil/water environment. Estimates of contaminant mobility are normally obtained using a parameter known as the K_d, which is a quantitative measure of the degree of sorption for an individual contaminant that exists between a solution and a solid phase under specific geochemical conditions. K_d values are used in contaminant transport equations to calculate migration rates for long-term predictions of contaminant movement and behavior in solution.

The value of K_d for each compound or element is a function of the geochemical behavior of that compound or element, as well as the composition and characteristics of the sorbent. In turn, the geochemical behavior of a compound is controlled by conditions such as redox potential (Eh), pH, and solution composition. Low K_d values indicate that contaminants are weakly sorbed to the solid phase resulting in a relatively high aqueous mobility through soils and sediments. Conversely, high K_d values indicate that contaminants are strongly sorbed to the solid phase resulting in a relatively low aqueous mobility through soils and sediments. Due to the variable conditions under which they were determined, the range of K_d values reported in the literature spans several orders of magnitude for the actinides.

The RFI/RI Report for OU3 at RFETS (DOE, 1996) reported the ranges of published values for uranium, plutonium, and americium as 0 to 4.4×10^3; 0.4 to 8.7×10^6; and 0 to 4.7×10^4, respectively (DOE, 1996). Representative K_d values given in the OU3 RFI/RI Report are 1.55×10^3 for U-234; 4.5×10^3 for plutonium; and 700 for americium (DOE, 1996). Many soil types occur at RFETS, and K_ds values will very among them. It remains to be determined whether it is possible to represent the K_ds for a specific actinide with a single value.

Jakubick (1976) estimated a K_d of 5×10^3 for plutonium in partially saturated, loamy soil with pH=6. The estimated vertical transport was 0.8 cm/yr. Jakubick (1976) suggested that PuO_2 migrated in the form of small discrete particles. If this is the case, then the migration rate of the plutonium would correspond to physical properties of a given soil. A study by

Routson et al. (1975) experimentally determined K_d values for americium. For soils in eastern Washington State, K_d values were greater than $1.2x10^3$, and were not influenced by different concentrations of calcium or sodium ions. Glover et al. (1976) conducted equilibrium sorption measurements on different soils for plutonium and americium nitrates. K_d values for plutonium nitrates ranged from 35 to $1.4x10^4$; whereas, those for americium ranged from 82 to $1x10^4$. Clay and sand content, along with cation-exchange capacity (CEC), were determined to be the most important factors in plutonium and americium immobilization or retardation in the soils suggesting that conventional ion-exchange processes were responsible.

One problem is the partially irreversible nature of sorption/desorption reactions. Experiments on the sorption of plutonium by red clay show that sorption/desorption reactions remain partially irreversible even after possible artifacts are accounted for (Higgo and Rees, 1986). The situation is further complicated by the mineralogical, physical, and chemical heterogeneity of soils. The problem of determining actinide partition coefficients (K_ds), therefore becomes one of determining the limited conditions most likely to represent natural conditions.

The Operable Unit 3 (OU3) RFI/RI Report (DOE, 1996) notes that the presence of multiple oxidation states and irreversible reactions between them makes the prediction of long-term behavior of plutonium in aquatic systems difficult. The report also states that environmental behavior of plutonium is complicated by the existence of ionic, particulate, and "colloidal and pseudo-colloidal plutonium" in the water column and notes that the adsorption of plutonium on sediments is not fully reversible, due to "colloid formation" and changes in the oxidation state. DOE (1996) also states that the K_d of plutonium may be lower under reducing conditions than under oxidizing conditions.

One method of estimating a K_d involves the calculation of values using data for soils and associated interstitial waters. The raw data to perform such calculations for RFETS have been evaluated for groundwater and surface water; unfortunately, dissolved results are close to or less than detection limits rendering the values highly uncertain.

K_d s for plutonium and americium in groundwater and surface water also may be calculated on the basis of total plutonium versus total suspended solids (TSS) and total americium versus TSS correlations. These determinations assume that (in the case of plutonium):

$$Pu(tot., pCi / L) = Pu(diss., pCi / L) + Pu(part., pCi / g) * TSS(g / L)$$

and

$$K_d = Pu(part.) / Pu(diss.)$$

The K_d value is then calculated by dividing the slope of the total Pu-TSS regression line (i.e., Pu[part.]) to the intercept value (i.e., Pu[diss.]) and correcting the result for proper units. These calculations result in estimated K_d values for plutonium and americium that are in the 10^3 to 10^5 L/kg range. The results are not presented here because further work is necessary to document the conditions under which the coefficients are valid and to systematically determine the errors associated with the determination.

Hursthouse and Livens (1993) used soil and interstitial water data to estimate K_d values for plutonium and americium in sediment profiles. Their K_d values ranged from 1.9 x 10^5 to 9.0 x 10^5 for plutonium and 11 x 10^5 to 39 x 10^5 for americium (Hursthouse and Livens, 1993).

As part of the 1997 Actinide Migration Studies, apparent K_d values will be determined for RFETS soils and sediments. The soils will be from the 903 Pad Lip Area and the SID, and the sediments will be from Ponds B-1, B-5, and C-2. These sorption studies are intended to supply empirical measurement for K_ds for conditions which are directly applicable to RFETS. The soil and sediment samples are chosen to represent the soil types most affected by plutonium. The water for laboratory experiments was obtained from monitoring wells at the Site and will contain anion and dissolved organic matter at concentrations representative of conditions at the site. Pu-242 will be used as a surrogate for the behavior of Pu-239 in soil. Proper precautions will be taken to ensure that Pu-242 is in correct valence during experiments and to prevent the problems with valence induced artifacts which affected earlier work. The importance of aging of actinides in soils on reversibility of sorption also Pu-239 should be investigated. The study should include a study of sorption and desorption kinetics of Pu-242 solutions onto and off of RFETS solid phases.

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4.0 ACTINIDE DISTRIBUTION AND TRANSPORT IN SOILS AND SEDIMENTS

This section presents a review of surface and subsurface soil and sediment sampling data for actinides collected at RFETS from 1990 through the present. Past studies of actinide distribution in the soils and sediments of RFETS are also cited and discussed. Section 4.3 discusses the transport of actinides by soil erosion processes and summarizes past erosion studies.

4.1 PLUTONIUM AND AMERICIUM IN SURFACE AND SUBSURFACE SOILS

Small amounts of plutonium and americium are found as background in all surface soils. Fallout from nuclear tests has contributed plutonium and americium to soils worldwide. These background levels are used as a benchmark at RFETS to determine which increased concentration-activities of americium or plutonium are due to Site activities. In general background subsurface soils have very small amounts of plutonium and americium, due to the limited mobility of these elements from surface soils.

4.1.1 Plutonium and Americium in Background Surface Soils

Surface soil is defined as the upper 6 inches (15 cm) of soil by the RFCA (DOE, 1996b). Background surface soils for RFETS are similar soils occurring on similar landscapes not influenced by plant activities. Concentrations of soil constituents in background soils have been determined to facilitate the identification of soils at RFETS with concentrations of chemicals of concern above background levels. Two background surface soil sampling programs have been completed at RFETS. Background surface soils samples were collected from the Rock Creek Area of the BZ, to the north of the RFETS IA. Results were reported in the *Background Geochemical Characterization Report* (BGCR) (DOE, 1993). The Background Soils Characterization Program was undertaken in 1994 (DOE, 1994a), due to on-going concern whether the Rock Creek soils are truly not influenced by plant activities and have representative background concentrations of radionuclides and other inorganic elements. Samples were collected in the Boulder County Open Space, just north of RFETS, and from 20 locations with soils similar to those of RFETS. Results of the program are presented in the *Geochemical Characterization of Background Surface Soils: Background Soils Characterization Program (BSCP) (DOE, 1995a).*

Results for the two sampling efforts were similar. The reported means and standard deviations for plutonium and americium are given in Table 4-1. Levels of plutonium in surface soils varied from 0.026 to 0.1 pCi/g in the BGCR (Rock Creek) data. In the BSCP data, surface soil plutonium levels ranged from 0.017 to 0.072 pCi/g. Americium surface soil levels ranged from 0.01 to 0.036 pCi/g in the Rock Creek data. In the BSCP data surface soil americium levels ranged from 0.001 to 0.025 pCi/g.

Table 4-1. Means and Standard Deviations for Plutonium and Americium in Background Surface Soil Data **(DOE, 1995a)**

Isotope	BGCR		BSCP	
	Mean	Standard Deviation	Mean	Standard Deviation
	pCi/g			
Americium-241	0.02	0.007	0.011	0.006
Plutonium-239/240	0.055	0.014	0.038	0.014

4.1.2 Distribution of Plutonium and Americium in Surface Soils

Plutonium and americium are generally not as mobile as uranium in the soil environment of RFETS (See Section 3.0). The primary mechanism of migration is physical transport of plutonium- and americium-contaminated surface soils by wind or water which has distributed these two actinides across the downwind and downslope soilscape (See Section 7). The spatial distribution of RFETS plutonium was estimated by two early studies (Krey and Hardy, 1970 and Seed et al., 1971). An aerial radiological survey was conducted in 1989 to measure both natural and anthropogenic gamma radiation from the terrain surface in and around the Site (EG&G, 1990). In 1990, an in-situ high purity germanium (HPGe) survey was conducted to the East of the 903 Pad Lip Area (EG&G, 1991). A second HPGe survey of the 903 Pad and Lip Area was performed in 1994 (RMRS, 1996). Several more recent studies of actinide distributions on and around RFETS have been published. These include: Litaor et al. (1994), Love (1994), Litaor et al. (1995), DOE (1995b), Litaor (1995a and 1995b), Litaor and Allen (1996a), and DOE (1996c).

Data were collected in support of remedial investigations for most former OUs, and these data are included in the data set used for the discussion that follows (DOE, 1994b, 1995b, 1996c, 1996d, 1996e, and others). Many other surface soil samples have also been collected at RFETS as part of various projects, namely; Bolivar et al., (1978); DOE, (1993, 1994a, and 1995a); EG&G (1990 and 1991); Hurr (1976); Krey and Hardy (1970); Krey et al. (1976); Litaor et al. (1994); Litaor et al. (1995); Litaor (1995a and 1995b); Litaor and Allen (1996a); Litaor and Ibrahim (1996b); RMRS (1996); Seed et al. (1971); and others. All surface soil data from the RFEDS have been compiled for the figures and discussion in this section. This data has not been tabulated due to the larger number of records, but a summary of the number of samples collected annually since 1988 is provided in Appendix A.

Plutonium concentration-activities in surface soils around RFETS range from 7,300 pCi/g near the 903 Pad, to background in many areas. Americium concentration-activities in surface soils range from background to 295 pCi/g, also in the 903 Pad Area. About 82 percent of the surface soil results for plutonium-239/240 and about 90 percent of the results for Am-241 are less than 1.0 pCi/g. Americium concentration-activities and spatial distribution show a high correlation to those of plutonium (DOE, 1995b).

Figures 4-1 and 4-2 show areas at RFETS with plutonium and americium concentration-activities estimated to be above 1 pCi/g. The contours were produced by kriging grids produced using analytical results reported for all surface soil locations shown in Figure 4-3. The reported analytical results for over 1,800 sampling locations taken from RFEDS were used. The contours were then examined and edited, using historical knowledge of radionuclide distributions. The figures show that surface soils with elevated concentration-activities for plutonium and americium occur to the east of the IA and within the Protected Area. The highest concentration-activities are associated with the 903 Pad and Lip Area corresponding to the area contaminated by wind and water transport of materials from the former 903 Storage Area (see Figure 4-4). An area of lower contamination surrounds the Solar Ponds. It is currently thought that this area was contaminated by windblown mists from the Solar Ponds. For this mapping effort soil samples taken from the top of the soil profile directly beneath the 903 Pad and the Solar Ponds were mapped as surface soil, although the areas are covered by a layer of asphalt. These contours agree closely with those produced by Litaor (1995a) and Litaor et al. (1995).

Figure 4-3 presents the results of screening all surface soil and sediment data available from the RFEDS against the radionuclide action levels developed for the ALF (DOE, 1996). The radionuclide action levels for surface soil incorporate a two-tiered approach. Tier II action levels are the activity-concentration that would yield a 15 mrem annual radiation dose to a hypothetical resident. Tier I radionuclide action levels for surface soils are calculated separately for the BZ and the IA. The Tier I action levels for the BZ are based on an 85 mrem annual radiation dose to a hypothetical resident. The Tier I action level for the IA is based on a 15 mrem annual radiation dose to an office worker. Table 4-2 shows the surface soil action levels for each radionuclide. The maximum analytical result for each radionuclide, at each location, was divided by the appropriate action level. The resultant ratios were then summed across radionuclides for each location, to obtain the action level sum of ratios, as described in the *Action Levels for Radionuclides in Soils for the Rocky Flats Cleanup Agreement* (DOE, 1996) and shown below.

$$\text{Sum of Ratios} = Pu_r/Pu_{al} + Am_r/Am_{al} + U234_r/U234_{al} + U235_r/U235_{al} + U238_r/U238_{al}$$

Where subscript 'r' denotes an analytical result, and subscript 'al' denotes the appropriate surface soil action level (Table 4-2). A sum of ratios was calculated for the ratio of a result to both the Tier I and Tier II action levels. If the sum of ratios calculated using the Tier I action levels for the five actinides was greater than or equal to one, then the location was plotted as 'above Tier I' (Figure 4-3); if the Tier I sum was less than one, then the sum for the Tier II ratios was used. When the Tier II sum of ratios was greater than one, the location was plotted as 'above Tier II but below Tier I', and when the Tier II sum was below one, the location was plotted as 'below Tier II'.

By comparing Figure 4-3 to the contour maps (Figures 4-1, 4-2, 4-9, 4-10, and 4-11), it can be determined which Tier I exceedances are mainly due to plutonium and americium. The exceedances of Tier I and Tier II action levels due mainly to plutonium and americium are in the area influenced by the 903 Pad. Exceedances in the other areas are mainly due to uranium isotopes which are discussed in Section 4.2.

Table 4-2 Radionuclide Surface Soil Action Levels (DOE, 1996a)

Radionuclide *(pCi/g)*	Tier I Action Level BZ	Tier I Action Level IA	Tier II Action Level Site-Wide
Americium-241	215	209	38
Plutonium-239/240	1429	1088	252
Uranium-234	1738	1627	307
Uranium-235	135	113	24
Uranium-238	586	506	103

4.1.3 Plutonium and Americium in Background Subsurface Soils

The BGCR also presents results of background subsurface soil sampling. Samples were taken to the north and south of the IA, well out of the zone of influence of plant activities. In samples of background subsurface materials from the upper hydrostratigraphic unit (includes alluvium, colluvium, weathered bedrock, and hydraulically connected sandstones), plutonium and americium are virtually at the limit of detection with the error terms as large or larger than the results (DOE, 1993). For statistical and reporting purposes all results are considered detections, although they may be below the detection limit. Reported concentration-activities for plutonium in subsurface soils ranged from -0.01 to 0.03 pCi/g, with a mean of 0.004 (standard deviation=0.007 pCi/g). Americium activity/concentrations in subsurface soils ranged from -0.015 to 0.01, with a mean of 0.00 pCi/g (standard deviation=0.007 pCi/g).

4.1.4 Distribution of Plutonium and Americium in the Subsurface Soils

Subsurface soil samples have been collected from boreholes drilled for many projects at RFETS. The samples are well distributed across the Site (Figure 4-5). Samples have also been collected from trenches and pits, specifically excavated for sampling purposes as part of the OU2 RFI/RI (DOE, 1995b and Litaor et al., 1994). All subsurface soil data from RFEDS were used in this section and a summary of annual number of samples collected is provided in Appendix A.

Figure 4-5 shows borehole, trench, pit, and well locations at RFETS where subsurface soil samples were collected. Plutonium concentration-activities in subsurface soils around RFETS range from background to 1,486 pCi/g in the East Trenches Area. Americium concentration-activities in subsurface soils range from background to 208 pCi/g in the East Trenches Area.

Locations with concentration-activities above Tier II or Tier I radionuclide action levels are shown in Figure 4-5. The same action levels are currently applied to subsurface soils for evaluation as for surface soils (Table 4-1). The method used to produce the ratios for subsurface soils depicted in Figure 4-5 was the same as explained above for surface soils (Figure 4-3). Results show that the areas with the highest concentration-activities are located in the East Trenches Area (near IHSS 110 [trench T-3] and in IHSS 111.4 [trench T-7]); to the west of the Original Landfill in and around IHSSs 133.1, 133.3, and 133.4; and in the area to the east of the Present Landfill.

Results from the sampling of the test trenches (not waste burial trenches) excavated in support of the former OU2 RFI/RI (DOE, 1995b, Litaor et al. 1994, and Litaor, 1995a and 1995b) make it possible to examine the distribution of americium and plutonium in surface and subsurface soils in the 903 Pad and Lip Area. The trench/pit locations are shown in Figure 4-6. Profiles for three representative trenches, with greatly varying concentration-activities of americium and plutonium, are shown in Figures 4-7 and 4-8. The distributions are very similar for americium and plutonium at all concentration-activities. Krey and Hardy (1970) also noted, "...an apparent similarity in the downward transport mechanism at all sites." Litaor et al. (1994) noted that in one trench (number 5) there was a translocation of actinides to greater depth than in other trenches. This location was characterized by a courser textured soil and a higher hydraulic conductivity than all other sites, these factors appeared to facilitate the downward movement of the actinides.

The actinide contamination in the 903 Pad Area originated from releases in the 903 drum storage area (the present 903 Pad) from 1958 to 1967, as described in Section 2.5. Contamination from the releases was then distributed to the south and east of the storage area by wind and surface water runoff. The soil profile data show the results of all combined migration factors that have been active since the plutonium was deposited in the surface soil. These include preferential flow of infiltrating water in decayed root channels (macropores) and the burrowing activities of earthworms, ants and other microfauna (Litaor et al., 1994).

Figure 4-7. Depth Distribution of Americium-241 in Soils Near the 903 Pad

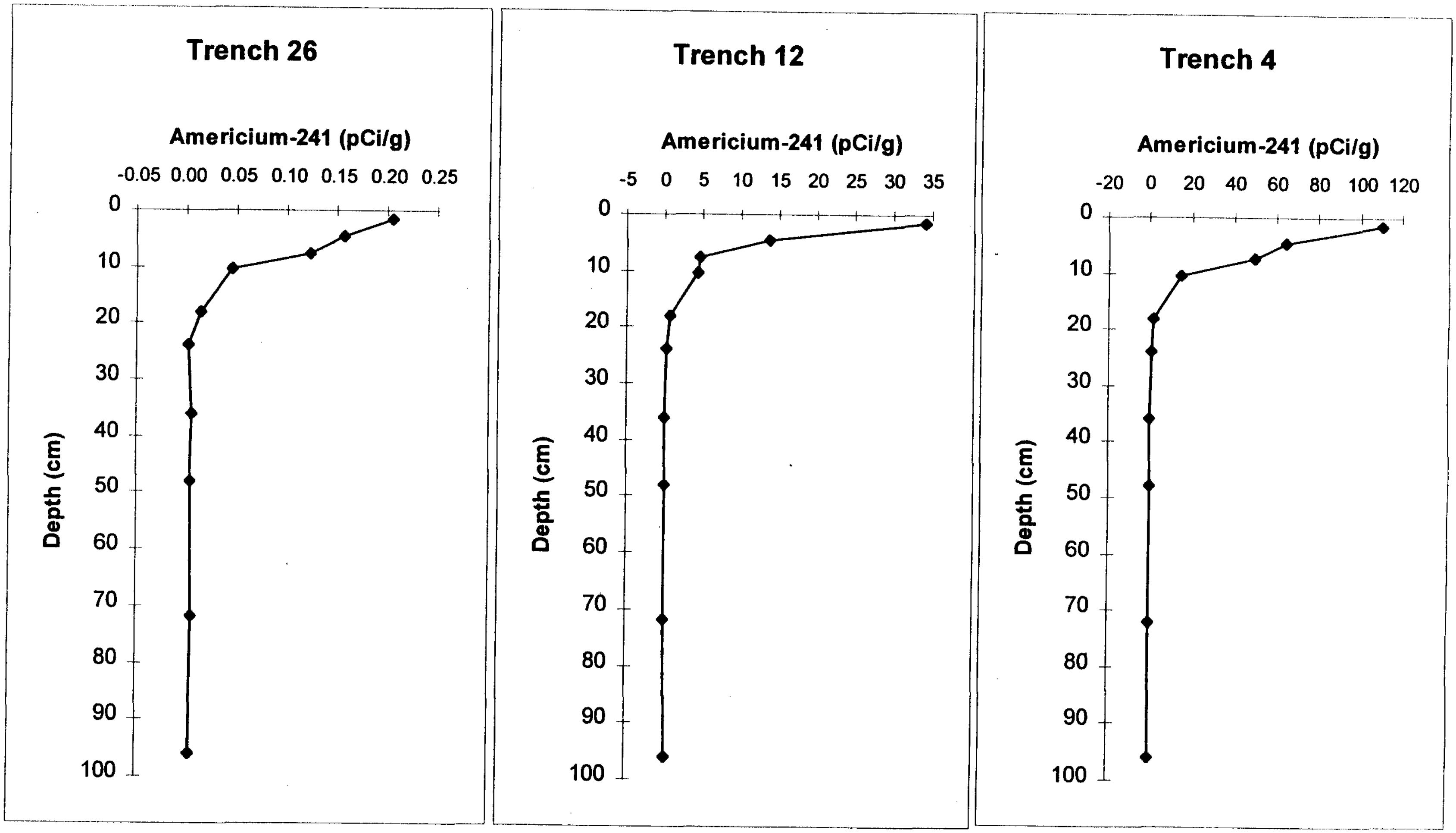
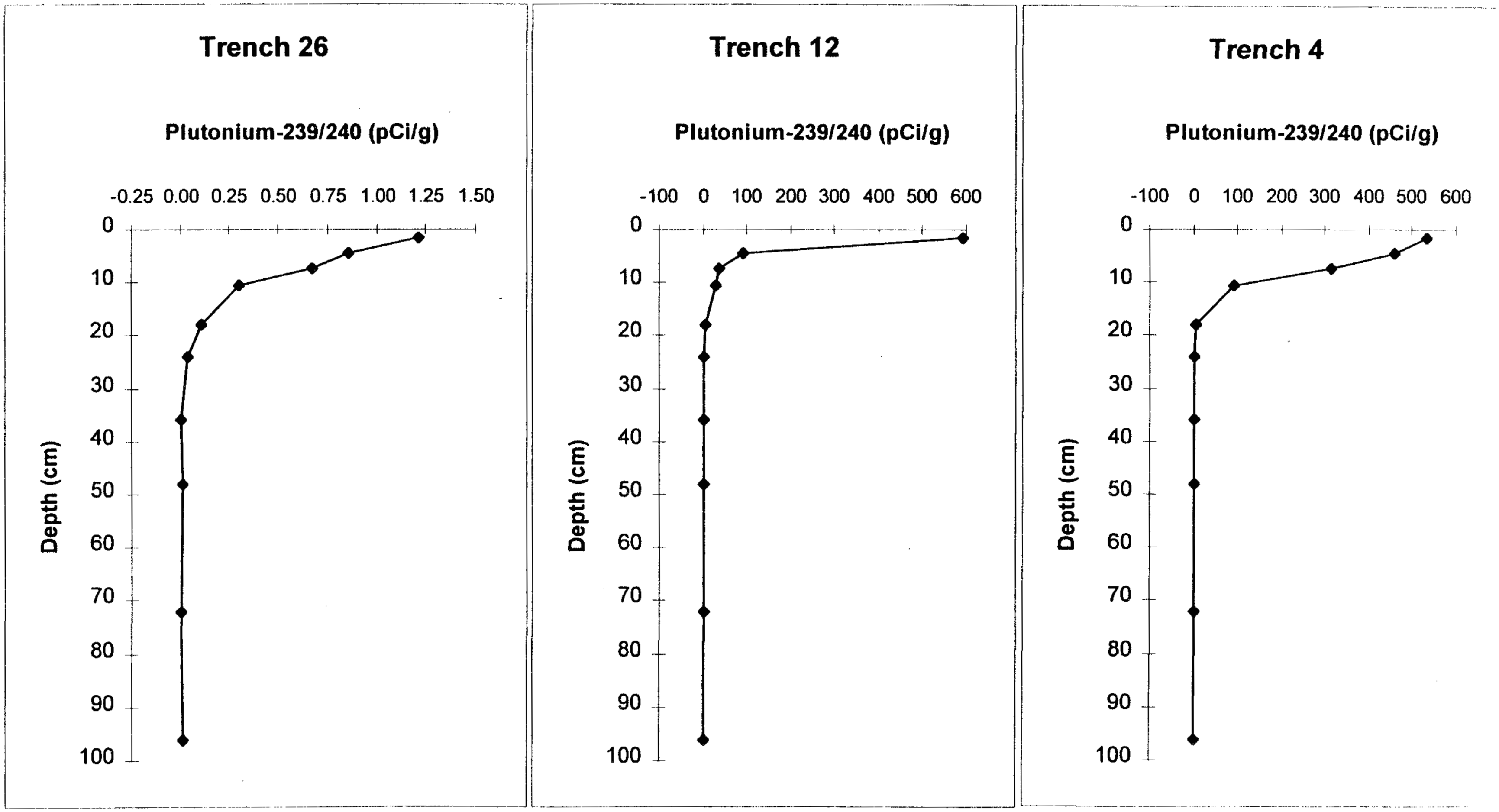


Figure 4-8. Depth Distribution of Plutonium-239/240 in Soils Near the 903 Pad



There has been little movement of plutonium and americium below a depth of 20 cm (about 8 in) during the 25 years since the release occurred, even with very high surface soil activity-concentration. This agrees well with the findings of Krey et al. (1976). Litaor et al. (1994) found that "90 % of the actinide activity in soils at the Site occurs in the upper 12 cm of the, regardless of soil series, or distance and direction from the source." Litaor et al. (1996c) also state that "the movement of actinides was restricted to the top 20 cm" of soil.

4.2 URANIUM IN SURFACE AND SUBSURFACE SOILS

Bolivar et al. (1978) evaluated uranium distributions in waters and sediments of the Front Range and speculated that "...higher uranium concentrations in water samples...are probably due to leaching of uraniferous strata in the Pierre and Laramie formations..." This same study noted that the granites of the Front Range "...are known to be rich in uranium..." and that the South Platte River is "...anomalously rich in uranium compared to most other rivers of its size." The types of rocks in the RFETS area (claystones of the Laramie Formation and Precambrian granites), the presence of nearby ore-grade uranium deposits (i.e., the Schwartzwalder mine), and a generally alkaline and oxidizing environment in the near-subsurface soils, contribute to the likelihood of high and variable concentrations of uranium existing in soils in the RFETS area.

4.2.1 Uranium in Background Surface Soils

Data compiled for the BGCR (DOE, 1993) and the BSCP (DOE, 1995a) gave very similar results for the mean concentration-activities for uranium isotopes in surface-soil samples collected from background areas near RFETS. The means and standard deviations from the two data sets for uranium-233/234, -235, and -238 are presented in Table 4-3. The distributions for all the uranium isotopes were determined to be lognormally distributed.

Table 4-3. Means and Standard Deviations for Uranium Isotopes in Background Surface Soil Data

Isotope	BGCR		BSCP	
	Mean	Standard Deviation	Mean	Standard Deviation
	pCi/g			
Uranium-233/234	1.145	0.156	1.097	0.578
Uranium-235	0.053	0.033	0.054	0.020
Uranium-238	1.183	0.188	1.090	0.455

4.2.2 Uranium in Background Subsurface Soils

Subsurface soils include soils and geologic materials from the upper hydrostratigraphic unit (includes alluvium, colluvium, weathered bedrock, and hydraulically connected sandstones) collected from depths below 6 inches from the soil surface. For subsurface soils (boreholes) at RFETS, means and standard deviations for uranium isotopes were calculated from data presented in the BGCR (DOE, 1993). The background means and standard deviations for U-233/234,-235, -238 are shown in Table 4-4.

Table 4-4. Means and Standard Deviations for Uranium Isotopes in Background Subsurface Soil Data

Isotope	BGCR	
	Mean	Standard Deviation
	pCi/g	
Uranium-233/234	0.779	0.932
Uranium-235	0.022	0.046
Uranium-238	0.733	0.376

4.2.3 Uranium in Surface Soils

Analytical data for uranium in surface soil samples collected across RFETS show a wide range of uranium isotope concentration-activities: uranium-233/234 concentration-activities in surface soils at RFETS range from 0.218 pCi/g to 2,800 pCi/g, concentration-activities for uranium-235 range from -0.02 pCi/g to 670 pCi/g, and uranium-238 concentration-activities ranged from 0.25 pCi/g to 3,800 pCi/g. Figures 4-9, 4-10, and 4-11 show the distribution of the uranium isotopes in surface soils at RFETS. Elevated concentration-activities for uranium are found around the Original Landfill (IHSS 115) and the Solar Ponds. The exceedances of Tier I and Tier II action levels in these areas (Figure 4-3) are due to the elevated uranium isotope concentration-activities.

Litaor (1995b) studied the soils east of the RFETS IA, downwind of the 903 Pad, and concluded that concentration-activities for all uranium isotopes were well within the natural range for soils. He further stated that, "Proposed wind-dispersal mechanisms were not consistent with the spatial distribution of U isotopes..." in surface soils east of the 903 Pad, and that there was, "...no clear relationship between known uranium burial and spill sites, and the present distribution of U-235 in the soils." He noted that the, "...lack of similarity in spatial distribution between Pu-239+240 and U isotopes probably resulted from the higher solubility and leachability of U isotopes compared with Pu-239+240 in the soil system." This may also have been due to differences in sources.

Isopleth maps of the uranium isotopes concentration-activities in surface soils support the above conclusion that the uranium concentration-activities of most of the soils are within the natural range (Figures 4-9, 4-10 and 4-11). It is true no elevated U-235 concentration-activities occur in surface soils to the east of the 903 Pad (Figure 4-10); however, there is an area of elevated U-238 activity to the east of the 903 Pad that correlates with the areas of highest americium and plutonium concentration-activities (Figures 4-1, 4-2, and 4-11). There are elevated concentration-activities of uranium isotopes in other known source areas, such as the Original Landfill, the Ash Pits, and the Solar Ponds. The lack of a well-defined spatial distribution of the uranium isotopes to the east of the 903 Pad, compared to plutonium and americium, may be due to their initially lower concentration-activities in the materials released, as well as to their higher solubility. This may have allowed the uranium isotopes to be redistributed within the soil profile.

4.2.4 Uranium in Subsurface Soils

Minimum and maximum values for uranium isotopes in samples of subsurface soils (subsurface materials from below 6 inches) at RFETS are displayed in Table 4-5. The maximum values are considerably higher than those obtained for samples collected from background areas onsite (DOE, 1993a).

Table 4-5. Minimum and Maximum Concentration-activities for Uranium Isotopes in RFETS Subsurface Soil Data

Isotope	minimum	maximum
	pCi/g	
Uranium-233/234	0.21	2875
Uranium-235[1]	-0.023	288
Uranium-238	0	24790

1 A negative result indicates that the reading was below the background reference value for that analysis.

Figure 4-5 shows the subsurface soil sampling locations and where radionuclide action levels are exceeded. The exceedances in the areas of the Original Landfill (IHSS 115), the Present Landfill (IHSS 114), and some locations in the East Trenches Area are due to elevated uranium concentration-activities. The high concentration-activities of uranium in these areas are likely due to buried contamination rather than the leaching of surface deposited uranium into the subsurface soil. However, uranium is subject to dissolution and leaching in the near-neutral, generally oxidizing environment found at RFETS, and is more geochemically mobile than plutonium and americium (as previously discussed in Section 3). This will be discussed in Section 5 relative to elevated concentration-activities of uranium in the Solar Pond Area.

Soil-profile studies performed in support of the OU2 RFI/RI indicated uranium leached downward under the RFETS 903 Pad (Litaor, 1995b). Figures 4-11 and 4-12 show the vertical distribution of U-233/234 and U-238 in soils near the 903 Pad Area. The uranium concentration-activities are very close to background levels (Section 4.2.2). Trenches 4 and 12 had high concentration-activities of plutonium and americium in the surface soil (Figures 4-7 and 4-8), but do not show a clear relationship of uranium activity-concentrations with depth. This may be indicative of naturally-occurring uranium or surficially-deposited uranium that have been redistributed in the soil profile due to its higher mobility.

4.3 SOIL EROSION AND TRANSPORT OF ACTINIDES TO SURFACE WATER/SEDIMENTS

The soil action levels (DOE, 1996a) for actinides did not consider transport pathways to surface water, surface water ingestion, or the long-term protectiveness of surface water quality. Data presented in Section 6 will describe actinide mobility in surface waters during storm events. Surface water exceedances have recently been reported in samples collected from Walnut Creek near Indiana Street. The overland transport of actinide contaminated soils to surface water has the potential to mobilize actinides in the Walnut and Woman Creek drainages.

4.3.1 Actinides in Background Stream Sediments

The concentration-activities of actinides in stream sediments was estimated using samples from nine locations in the Rock Creek and upper Woman Creek drainages that are considered out of the zone of influence of Site activities (DOE, 1995a). These were the

Figure 4-12. Depth Distribution of Uranium -233/234 in Soils Near the 903 Pad

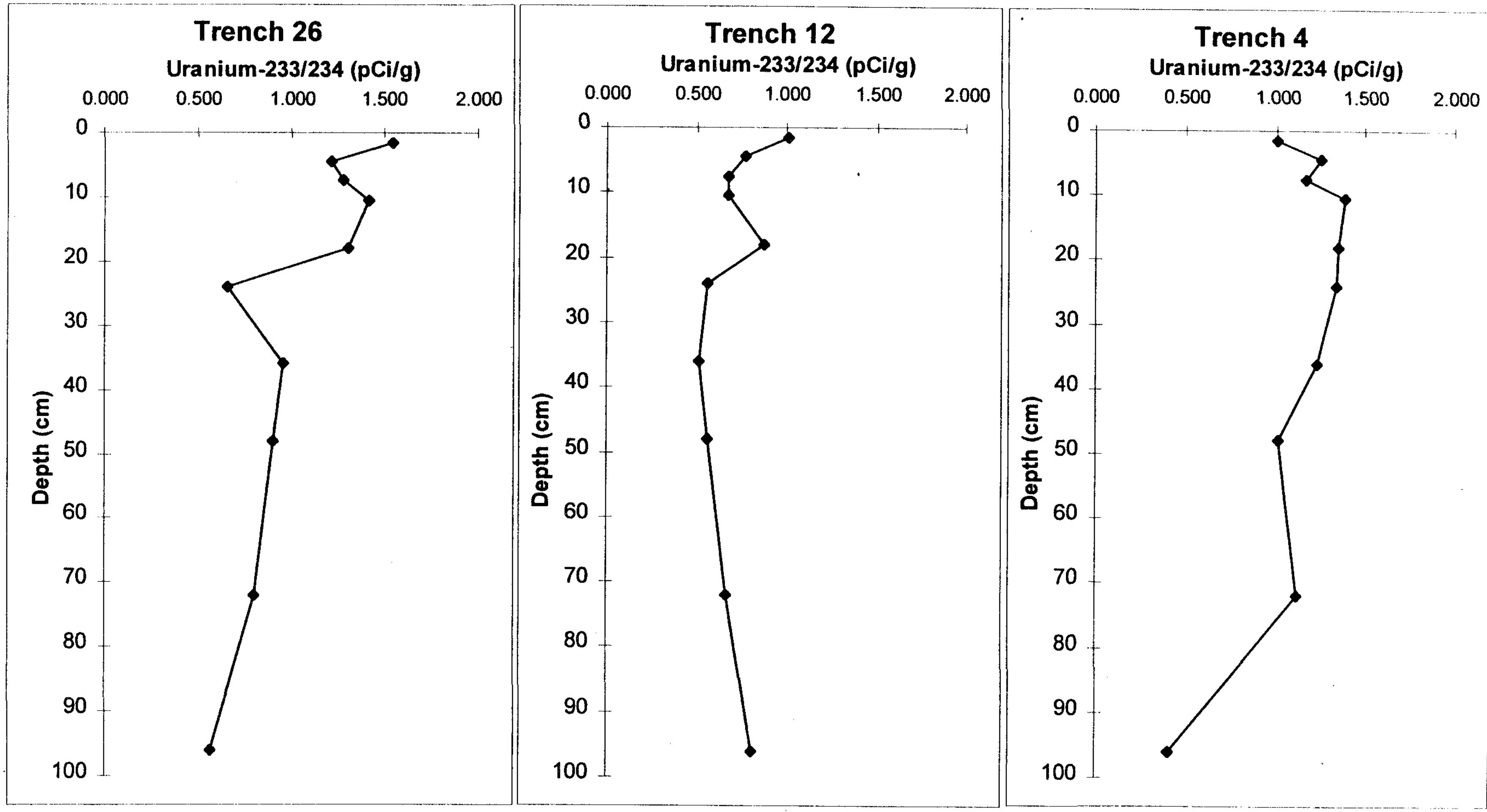
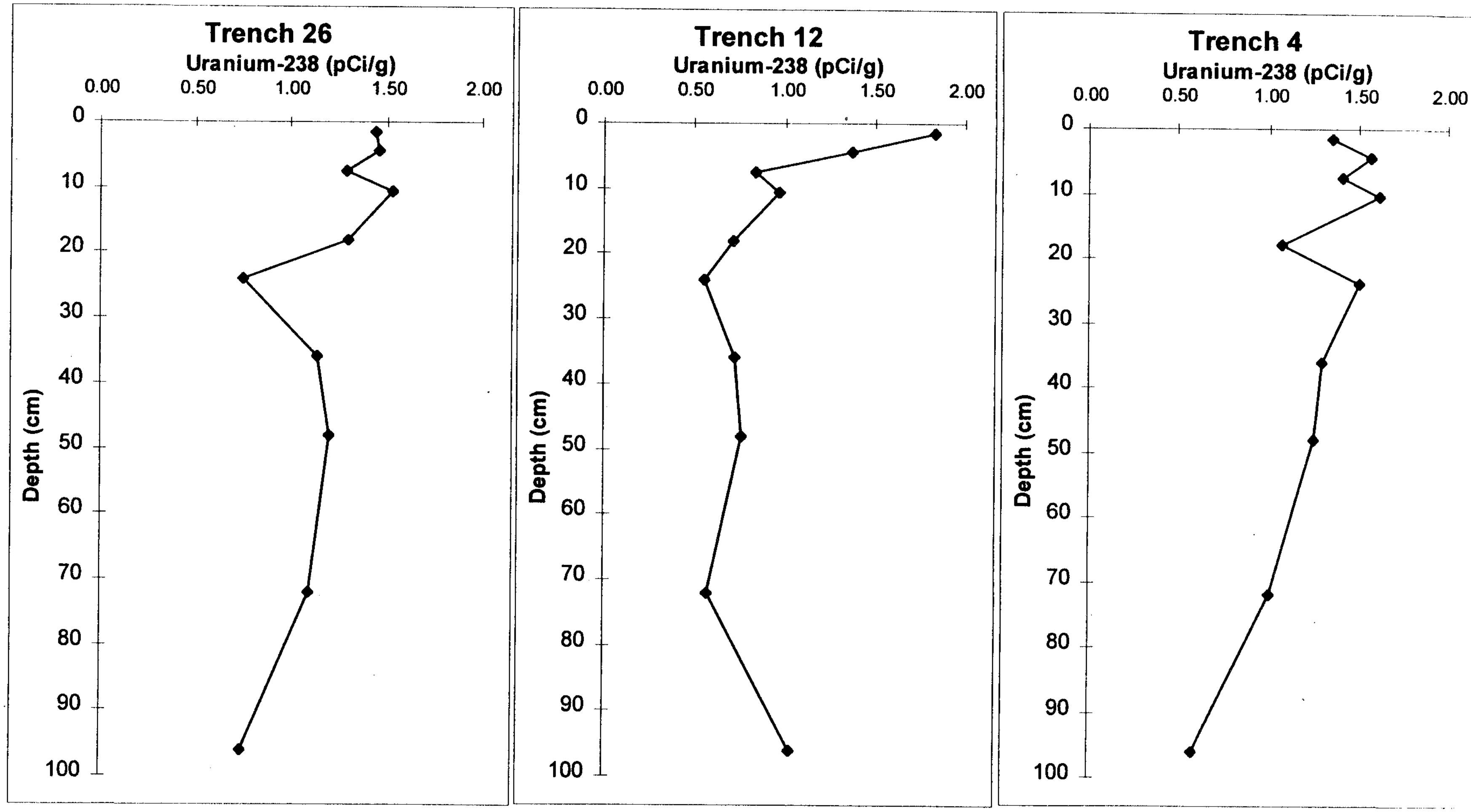


Figure 4-13. Depth Distribution of Uranium-238 in Soils Near the 903 Pad



same locations that were used for background surface water sampling. The sites were selected to be representative of the lithologies present in the drainages of the Site. The means and standard deviations for the background samples are shown in Table 4-6.

Table 4-6. Means and Standard Deviations for Actinides in Background Stream Sediments (DOE, 1995a)

Isotope	Observations	Mean	Standard Deviation
		pCi/g	
Americium-241	35	0.07	0.19
Plutonium-239/240	42	0.17	0.59
Uranium-233/234	47	1.68	2.69
Uranium-235	49	0.06	0.10
Uranium-238	36	1.40	2.60

The background values for sediments are higher than for surface soils. This is an expected phenomenon. Sediments generally have higher concentrations than the parent soil for a range of metals and radionulcides due to the transport of the finer particle sizes to depositional areas by erosion and overland flow. This process is known as enrichment.

4.3.2 Actinides in Sediments

Figure 4-3 shows areas with sediment concentration-activities above the Tier I and Tier II surface soil action levels. Concentration-activities above the Tier II action levels are found in Ponds B-1, B-2, and B-3 (DOE, 1996e). These high levels are due to waste streams entering the ponds, not the erosion and transport of soil to the ponds (see the Historical Release Report, DOE, 1992). Concentration-activities in the stream drainages are generally in the 0.01pCi/g to 0.3 pCi/g range (DOE, 1996c, 1996d, 1996e). Stream sediments in the Walnut Creek drainage are currently being sampled and analyzed to provide information to determine the causes of the recent exceedances surface water standards.

The relationships among surface soil, stream sediment, and surface water concentration-activities are not well understood. A better understanding of these relationships in the two major drainages on the Site must be developed to ensure the long-term protection of surface water. The purpose of modeling soil erosion by water for the watersheds at RFETS is to estimate the long-term transfer of soil- and sediment-bound actinides from soil to stream sediments to surface water under a variety of plausible future scenarios, to provide information for the conceptual model, and to facilitate the choice of cleanup levels for actinides in surface soils that are protective of surface water under long-term conditions.

4.3.3 Past Erosion Modeling Efforts

Surface soil in the 903 Pad Area is one of the major contaminant sources for the Woman Creek drainage. Precipitation events induce soil movement and surface soils and associated actinides are carried by overland flow to surface water drainages. Two reports have used the Universal Soil Loss Equation (USLE) model, developed by the USDA (Renard et al., 1997), to estimate soil movement in the 903 Pad Area, *Estimated Soil Erosion and Associated Actinide Transport for the South Interceptor Ditch Drainage (DOE, 1992)* and *Phase II RFI/RI Report, 903 Pad, Mound, and East Trenches Area, Operable Unit No. 2* (DOE, 1995).

The 1992 report (DOE, 1992) modeled soil erosion and associated transport of soil-bound actinides within the SID drainage basin. Its purpose was to assess the impact of 881-Hillside construction and SID maintenance activities on soil erosion and the transport of actinides to Pond C-2 via the SID. The hillside on the south side of the IA, from west of the Original Landfill to Pond C-2 was divided into seven sub-basins for the study. The total annual quantity of soil transported into the SID was estimated using the RUSLE and the EPA Storm Water Management Model (SWMM) and t Sediment Removal Model (SRM) were then used to estimate sediment movement in the SID and to Pond C-2 during pre- and post-maintenance conditions.

The 1995 study (DOE, 1995), performed as part of the OU2 RFI/RI, used the MUSLE estimated soil erosion from the 903 Pad, Mound, and East Trenches Area and estimated loading to the South Walnut and Woman Creeks. The purpose of the study was to estimate concentrations of chemicals of concern in the Walnut and Woman Creek drainages at Indiana Avenue over a 30-year period. The study assumed that no engineered structures, such as Pond C-2, were present. For modeling, 65 small sub-basins were delineated, to produce sub-basins of roughly uniform gradient meeting the model criteria. Concentration-activities of americium and plutonium were estimated over the entire area using data from 1991 soil sampling events.

The RUSLE model has been evaluated. The documentation, databases used for calculations, and the computer model have been recently updated (Renard et al., 1997). The RUSLE is an empirically-based erosion model predicting long-term average annual soil loss resulting from rainfall and runoff for a variety of field conditions including rangeland. Its development and widespread use over a period of 40 years has confirmed the RUSLE's usefulness and validity in quantitatively predicting soil loss and evaluating conservation practices. The soil loss computed by RUSLE is a guide, not a precise estimator of soil loss. It has limitations in scope. It is best used on a field scale rather than on a watershed scale. RUSLE has been used to estimate watershed sediment yields, however care must be taken to account for depositional areas on the landscape. The long-term average soil loss computed with RUSLE is not sediment yield from the field, but an estimate of total sediment production by sheet and rill erosion. Sediment yield may be much less or, if ephemeral gully erosion occurs, sediment yield may be much greater than estimated by

RUSLE. The model must be coupled with other models to estimate sediment transport within the drainages and concentrations at the Site boundary.

In the 1992 and 1995 studies it was assumed that all eroded soil remained suspended in the surface water flow. Therefore, soil loss was overestimated, as estimates of estimate sediment deposition were not included within each sub-basin. The plutonium activity concentrations for Woman Creek estimated in the 1995 were more than an order of magnitude greater than average observed values for the drainage. This indicates significant problems with the model, as used, leading to a gross overestimate of sediment loading to the drainage. There is a discussion of planned future erosion modeling efforts in Section 8.

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5.0 ACTINIDE DISTRIBUTION AND TRANSPORT IN GROUNDWATER

This section presents data on the distribution of actinides in both background and non-background monitoring wells at RFETS. Two background studies at RFETS have evaluated actinides in groundwater, the BGCR (DOE, 1993) and the draft Comparison for Radionuclides in Groundwater (DOE, 1997). Areas west, north, and south of the IA, that are hydrologically upgradient or sidegradient to the IA, are considered to be background areas (Figure 5-1). The background values reported by DOE (1993) included results from wells screened into the weathered bedrock, as well as in the alluvial and colluvial materials that lay above it. The 1997 study includes a larger number of wells and a longer sampling duration than the 1993 study. It was initiated to develop background values that are representative of the unconsolidated materials over laying the bedrock.

5.1 PLUTONIUM AND AMERICIUM IN BACKGROUND GROUNDWATER

The 1993 study (DOE, 1993) reported only three records for americium and one record for plutonium in filtered (0.45 μm) samples of background groundwater, none are above the current 0.15 pCi/L groundwater Tier II action level. The 1997 study (DOE, 1997) contains 24 and 28 filtered analyses for americium and plutonium, respectively (Table 5-1). None of these results are above the current action levels. Many more analyses are available for unfiltered or total samples. The maximum reported activity for americium in unfiltered samples of background groundwater in the 1993 study is less than the 0.15 pCi/L Tier II groundwater action level. In the 1997 study only the maximum value for americium was above the action level. Two plutonium samples of unfiltered background groundwater in the 1993 study were above the Tier II action level, and three were above the Tier II action level in the 1997 study (Table 5-1).

Table 5-1. Americium-241 and Plutonium-239/240 in Background Groundwater

	Obs.	Mean	Stand. Dev.	BG Bench-mark	Min.	Max.	Obs.	Mean	Stand. Dev.	Min.	Max.
	DOE, 1993						DOE, 1997				
	Filtered (pCi/L)										
Americium-241	24	0.003	0.005	0.013	-0.007	0.018	2	0.01	0.01	0.0	0.02
Plutonium-239/240	25	0.002	0.004	0.01	-0.004	0.014	1	0.01	--	0.01	0.01
	Unfiltered (pCi/L)										
Americium-241	275	0.006	0.015	0.036	-0.02	0.10	183	0.01	0.01	-0.01	0.19
Plutonium-239/240	289	0.005	0.021	0.047	-0.05	0.22	194	0.004	0.02	-0.01	0.22

5.1.1 Plutonium and Americium in Groundwater

Sitewide groundwater at RFETS shows a narrow range of activities in filtered samples for americium-241 and plutonium-239/240 with maximums of 0.47 and 2 pCi/L, respectively. The maximums for unfiltered americium and plutonium samples are 46.5 and 13.4 pCi/L, respectively. The highest activities for both plutonium and americium were measured in samples collected from the vicinity of the 903 Pad as shown in figures 5-2 and 5-3.

The maximums, minimums, means, and standard deviations for groundwater data collected from 1991 through 1996 for each location with filtered or unfiltered americium or plutonium activities above the groundwater action levels (DOE, 1996) are shown in Table 5-2 and are depicted in Figures 5-2 and 5-3. The figure shows a group of wells in the 903 Pad Area with elevated americium and plutonium activities in ground water samples. Activities in the sampled wells are generally below the background benchmarks (background mean plus two standard deviations) of 0.05 pCi/L for plutonium and 0.04 pCi/L for americium. Two wells (locations 09091 and 06991) have significantly higher average activities (Table 5-2). It is believed that the contamination is due to the movement of contaminated soil into the well-hole during drilling and localized around each well which has been documented in other wells (EG&G, 1995a). Since these wells were drilled, new technology has been developed at RFETS that eliminates the downward movement of contaminants in surface soil during

Table 5-2. Groundwater Sampling Locations with Maximum Filtered or Unfiltered Americium or Plutonium Isotope Concentration-Activities Greater Than the Tier II Action Levels[1].

Location	Max	Min	Mean	Std Dev.
Filtered (pCi/L)				
Americium-241				
09091	21.310	0.012	10.661	15.060
1286	0.471	0.471	0.471	
08891	0.435	0.435	0.435	
07191	0.148	0.148	0.148	
06991	0.264	0.008	0.136	0.181
Plutonium-239/240				
08891	1.999	1.999	1.999	
09091	0.813	0.149	0.481	0.469
11791	0.230	0.022	0.126	0.147
72393	0.330	-0.002	0.050	0.124
Unfiltered (pCi/L)				
Americium-241				
09091	46.540	1.400	11.177	14.662
06991	9.730	0.190	1.358	2.947
1286	1.087	0.272	0.680	0.576
P208989	5.289	0.000	0.546	1.667
07191	2.270	0.030	0.503	0.988
P115489	0.380	0.380	0.380	
2286	0.950	0.002	0.272	0.319
06691	0.580	0.160	0.266	0.176
11791	1.321	-0.010	0.253	0.359
P313489	0.250	0.250	0.250	
1587	0.650	0.015	0.246	0.229
05193	0.650	0.031	0.233	0.233
0271	0.381	0.066	0.223	0.223
0460	0.508	0.041	0.209	0.211
41691	3.200	-0.001	0.196	0.587
08891	0.550	0.010	0.168	0.170
3686	0.160	0.160	0.160	
72093	0.340	0.002	0.114	0.115
06591	0.270	0.022	0.113	0.077
13191	0.597	0.012	0.112	0.157

Table 5-2 (continued)

B204189	0.470	0.003	0.099	0.207
72393	0.221	0.003	0.086	0.079
12091	1.090	0.000	0.083	0.290
24993	0.150	0.003	0.077	0.104
34791	0.530	-0.015	0.050	0.159
59493	0.200	0.003	0.050	0.075
0987	0.450	0.000	0.045	0.116
09691	0.160	0.000	0.042	0.048
07391	0.340	-0.001	0.041	0.105
0487	0.324	-0.004	0.041	0.106
01991	0.375	-0.001	0.041	0.105
01491	0.230	0.000	0.038	0.068
7187	0.393	-0.000	0.031	0.104
B400289	0.190	0.002	0.030	0.070
B110989	0.161	0.000	0.016	0.044
Plutonium-239/240				
09091	354.6	12.0	94.6	21.8
06991	71.7	1.20	9.82	6.71
11791	13.360	-0.003	2.494	3.488
1286	3.650	0.699	2.174	2.087
B204189	10.320	-0.000	2.065	4.615
P313489	1.600	1.600	1.600	
06691	3.361	0.832	1.527	1.052
1587	4.300	0.510	1.510	1.218
06591	2.900	0.778	1.505	0.728
2286	4.820	0.000	1.327	1.724
13191	5.024	0.058	1.247	1.320
08891	3.400	0.034	1.052	1.064
0366	0.900	0.900	0.900	
0271	1.261	0.388	0.825	0.617
5671	0.470	0.470	0.470	
72093	1.200	0.008	0.402	0.393
41691	2.204	0.000	0.378	0.487
13491	0.870	0.130	0.343	0.264
72393	0.799	0.005	0.332	0.292
P209189	0.510	0.083	0.325	0.153
09691	1.100	0.048	0.298	0.295
0290	2.510	0.002	0.285	0.834
59493	1.037	0.001	0.261	0.385
00291	0.780	0.042	0.241	0.196

Table 5-2 (continued)

6387	0.386	0.121	0.233	0.097
00191	1.300	0.020	0.204	0.367
46792	0.530	0.000	0.189	0.296
3686	0.166	0.166	0.166	
0171	0.494	0.023	0.164	0.193
06891	0.290	0.084	0.154	0.083
02991	0.800	0.002	0.112	0.245
24993	0.210	0.009	0.110	0.142
00391	0.570	0.001	0.109	0.169
4286	0.269	-0.002	0.106	0.075
25093	0.200	0.008	0.104	0.136
46692	0.970	0.000	0.103	0.289
46892	0.480	0.001	0.097	0.190
1687	0.420	0.007	0.087	0.117
03091	0.350	-0.027	0.073	0.111
0374	0.199	0.000	0.067	0.114
05193	0.200	-0.009	0.065	0.068
0486	0.179	0.000	0.064	0.060
11891	0.208	0.007	0.058	0.069
20591	0.230	-0.001	0.058	0.115
04591	0.580	-0.001	0.052	0.147
22193	0.415	-0.001	0.049	0.137
01991	0.310	0.001	0.042	0.086
70093	0.215	0.000	0.037	0.073
0460	0.072	0.000	0.035	0.027
05191	0.170	0.003	0.030	0.047
07391	0.179	-0.004	0.028	0.058
3287	0.171	0.000	0.028	0.063
10991	0.232	0.002	0.027	0.060
03791	0.164	0.000	0.024	0.042
5186	0.347	-0.003	0.021	0.081
1490	0.182	-0.005	0.021	0.057
46192	0.235	-0.002	0.019	0.065
1786	0.210	-0.002	0.018	0.045
5086	0.254	-0.019	0.012	0.059

1 These locations are included in Figures 5-2 and 5-3.

drilling by excavating contaminated surface soil and sealing off the drilling area from further surface soil contamination prior to drilling (EG&G, 1995a). A method for determining the source of the contamination, and whether it is more widely distributed in the groundwater, is to develop new wells using the RFETS aseptic method.

Soils data (Section 4.0), knowledge of actinide behavior in the environment (Section 3.0), and groundwater data do not indicate that plutonium or americium are moving into and with the ground water at RFETS. Before any remediation decisions are made with respect to plutonium and americium in specific groundwater wells, one or more wells should be drilled using aseptic methods to determine the source and extent of the groundwater contamination.

5.2 URANIUM ISOTOPES IN BACKGROUND GROUNDWATER

Uranium isotopes in samples of filtered (0.45 μm) and unfiltered groundwater collected from the UHSU exhibit a wide range of reported activities (Table 5-3). The maximum values are from well B205589 which lies along the Rock Creek drainage, just south of Highway 128 (Figure 5-1). There is no evidence that this well has any anthropogenic contamination. This is confirmed by both the uranium atom and activity ratios (Table 5-5 and 5-6), which indicate the uranium is naturally occurring. These ratios are explained and their significance discussed in Section 5.2.2 and 5.2.3. This well, along with all other background wells, is located outside the area in which groundwater has been impacted by releases from RFETS.

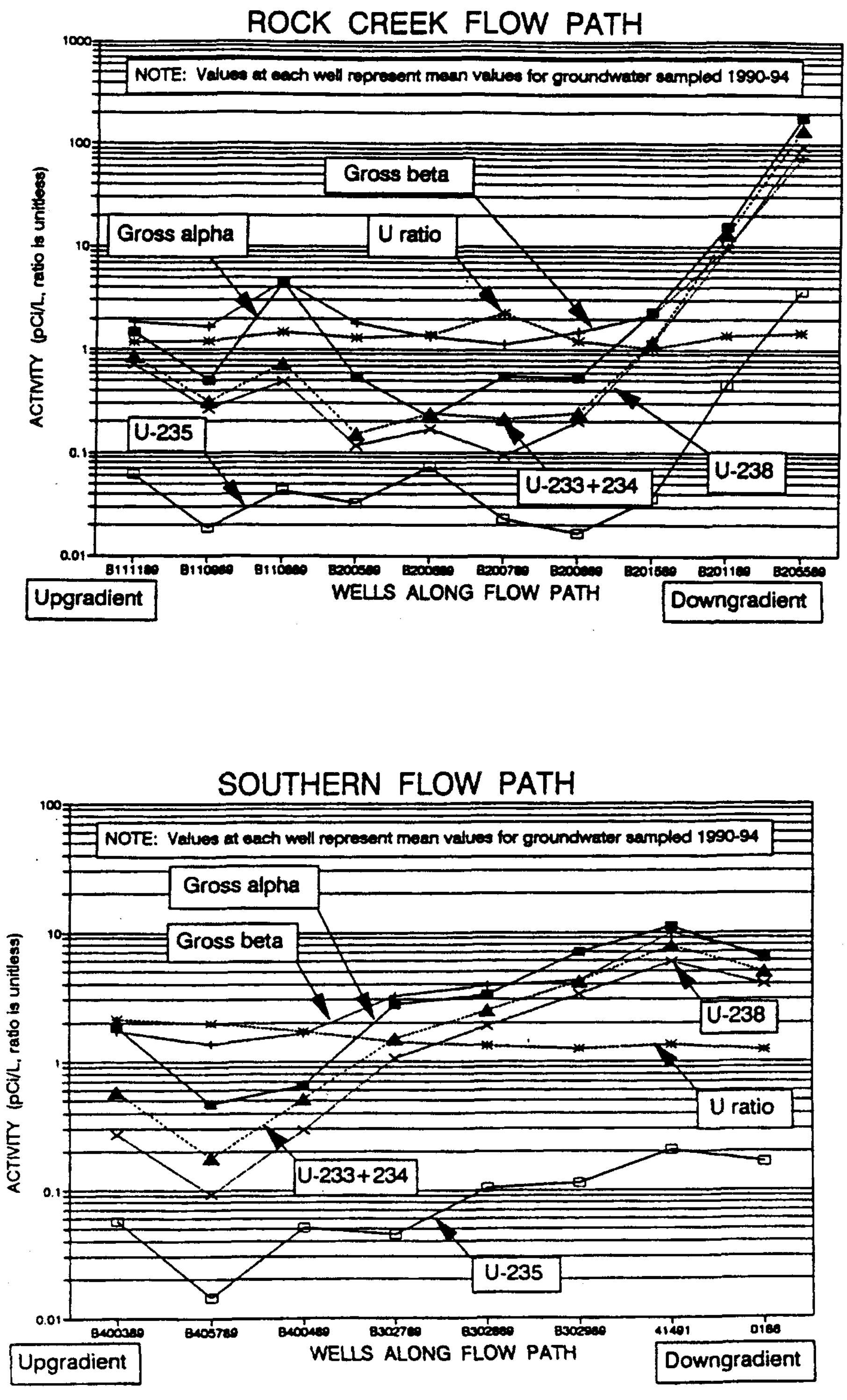
In addition to data from the 1993 and 1997 studies, evaluations were performed in the *Groundwater Geochemistry Report* (EG&G, 1995b) that show the geochemical evolution in the composition of shallow groundwater along flow paths at RFETS. For the Rock Creek and Southern flow paths (Figure 5-1), concentrations of dissolved uranium isotopes show an increase as water moves west to east along the flow path (Figure 5-4). The increase in

Table 5-3. Uranium Isotopes in Background Groundwater

	Obs.	Mean	Std. Dev.	BG Bench-mark	Min.	Max.	Obs.	Mean	Std. Dev.	Min.	Max.
	DOE, 1993						DOE, 1997				
	Filtered (pCi/L)										
Uranium-233/234	287	6.55	27.1	60.8	-0.078	199.5	207	6.91	25.4	-0.02	199.5
Uranium-235	288	0.023	0.78	1.58	-0.035	5.35	207	0.195	0.635	-0.04	4.80
Uranium-238	286	4.60	18.6	41.8	-0.04	135.6	177	4.83	17.7	-0.04	135.6
	Unfiltered (pCi/L)										
Uranium-233/234	39	14.7	35.3	85.3	0.0	164	35	15.6	38.75	0.0	164
Uranium-235	39	0.69	1.54	3.77	-0.01	6.48	35	0.617	1.38	-0.02	6.29
Uranium-238	41	10.5	24.9	60.3	0.0	108	22	10.8	27.7	0.0	108

dissolved uranium observed in the report (EG&G, 1995b) may be related to increasing levels of dissolved carbonate (which complexes with uranium to increase the solubility of uranium), or to naturally occurring accumulations of uranium. The ratio of uranium-238 to uranium-235 was shown to be consistently in the range of naturally occurring uranium.

The large variability shown for levels of uranium in background groundwater is expected, considering the inherent heterogeneity of geologic materials and the presence of ore-grade uranium deposits within 10 miles of RFETS (Schwartzwalder mine near Ralston Reservoir). A recent study performed by the Jefferson County Health Department (Moody and Morse, 1992) found high levels of uranium in the groundwater of Coal Creek Canyon, which is upgradient of RFETS. The Jefferson County study compiled data for groundwater samples collected from 33 domestic wells in Coal Creek Canyon. Uranium (total) ranged from 1.3 to 1,200 pCi/L, with a mean and standard deviation of 174.9 and 339.1 pCi/L, respectively.



U ratio = u238:u235

Figure 5-4. Background Dissolved Uranium Activities in Groundwater Along the Two Flow Paths at RFETS

5.2.1 Uranium in Groundwater at RFETS

Analytical data for uranium in groundwater samples collected across RFETS show a wide range of uranium isotope activities. The maximum activities in groundwater samples during the years 1991 through 1996 for filtered and unfiltered samples are: uranium-233/234, 492 and 92.2 pCi/L; uranium-235, 35.7 and 6.48 pCi/L; and uranium-238, 325 and 101 pCi/L. The RFETS background mean plus two standard deviations, which is used as a screening benchmark for ground water evaluations at RFETS, is equal to 60.8 and 85.3 pCi/L, 1.78 and 3.77 pCi/L, and 49 and 60.3 pCi/L for filtered and unfiltered uranium-233/234, -235, and -238 respectively (Table 5.3 and DOE, 1997). The maximum values for each isotope are all above the background benchmarks. Table 5-4 shows all locations with filtered (dissolved) and unfiltered (total) uranium isotope activities in groundwater above the background benchmarks. The maximums, minimums, means, and standard deviations are given for data collected from each location from 1991 through 1996.

Figures 5-5 through 5-7 show the distribution of dissolved (filtered) uranium isotope concentration-activities across the Site. The groundwater monitoring data collected over the past seven years contain a preponderance of dissolved uranium analyses rather than total (unfiltered) analyses. The reason for this is that DOE and CDPHE have formerly agreed that groundwater action levels for uranium apply to dissolved uranium isotopes. The mean activity for each sampling location over the period from January, 1991 through December, 1995 was used for plotting. This data is being used as a baseline for groundwater evaluations under the Integrated Monitoring Plan (DOE, 1997b).

Uranium 233/234 concentration-activities above the Tier II action level of 1.07 pCi/L have been found across RFETS (Figure 5-5). However, the background benchmark mean plus two standard deviations is 60.7 pCi/L. Values above the benchmark only occur in the Solar Ponds area and downgradient towards North Walnut Creek. This is the area with a known

Table 5-4. Groundwater Sampling Locations with Unfiltered and Filtered Uranium Isotope Concentration-Activities Greater Than the Background Benchmark[1].

Location	Max	Min	Mean	Std Dev
Unfiltered (pCi/L)				
Uranium-235				
10294	6.48	1.40	3.21	2.24
59993	4.00	0.306	2.15	2.61
Uranium-238				
61093	101	0.026	47.3	40.0
10294	69.5	25.0	43.5	20.7
P114989	68.0	68.0	680	--
Filtered (pCi/L)				
Uranium-233/234				
05093	492	56.0	221	131
2886	280	74.5	141	65.8
05193	258	136	199	34.3
B205589	180	2.45	121	51.8
B303089	150	120	135	21.2
3086	139	37.1	98.2	20.5
B305389	134	2.70	22.1	49.3
2689	95.1	95.1	95.1	--
B208689	83.5	69.0	72.9	4.32
05393	81.1	81.1	81.1	--
B210389	80.9	80.9	80.9	--
P208989	73.0	1.73	59.1	19.4
0586	63.0	19.1	39.5	22.1
Uranium-235				
05193	35.7	5.40	10.5	9.12
05093	27.7	1.70	9.53	8.00
2886	11.0	2.32	4.59	2.92
5287	9.12	0.54	1.73	2.09
3086	8.03	2.47	4.31	1.65
B303089	6.90	4.00	5.45	2.05
B210489	5.61	0.508	1.36	1.26
B205589	5.54	0.035	3.66	1.76
2686	5.04	0.538	1.44	1.28
10294	4.25	0.770	2.20	1.32
B208689	4.10	1.00	2.19	0.890
05393	3.64	3.64	3.64	
B305389	3.21	-0.011	0.504	1.19
1586	2.91	0.360	0.833	0.606
35691	2.51	0.290	0.730	0.578
P209889	2.50	0.737	1.35	0.519
P208989	2.40	0.016	1.57	0.609

Table 5-4 (continued)

37791	2.30	-0.007	0.861	0.550
10692	2.25	0.279	0.68	0.560
B210389	2.19	2.19	2.19	--
0586	2.10	0.578	1.35	0.761
P209489	2.09	0.835	1.37	0.392
1786	2.02	0.744	1.32	0.336
01391	1.99	0.120	0.532	0.560
2187	1.99	0.629	1.17	0.622
06491	1.95	0.630	1.13	0.515
P210289	1.94	1.94	1.94	--
B206589	1.90	0.530	1.01	0.416
B208589	1.90	1.03	1.37	0.463
37191	1.83	0.047	0.483	0.432
Uranium-238				
05093	325	39.0	144	87.3
2886	200	46.3	95.6	48.8
05193	126	62.2	90.4	19.6
B205589	121	2.23	84.3	35.1
B303089	120	110	115	7.1
3086	91.5	24.4	63.9	12.6
B305389	89.3	1.60	14.6	32.9
61093	80.8	9.80	39.2	37.1
07391	75.7	18.9	33.9	14.3
05393	66.4	66.4	66.4	--
B208689	54.0	42.0	47.7	3.49
B210389	49.9	49.9	49.9	--
P208989	48.0	0.50	37.7	12.8

1. The background bench marks for unfiltered and filtered samples are; uranium-233/234 = 85.3 and 60.7 pCi/L, uranium-235 = 3.76 and 1.79 pCi/L, and uranium-238 = 60.3 and 41.8 pCi/L. No unfiltered uranium-233/234 results were above the benchmark. These locations are included in Figures 5-5, 5-6, and 5-7.

nitrate plume extending from the Solar Ponds toward North Walnut Creek. The presence of high nitrate concentrations in the ground water may increase the mobility of the uranium (See Section 3.0).

Uranium-235 concentration-activities above the Tier II action level of 1.01 pCi/L are not common, but are found in background wells and also in areas affected by Site activities (Figure 5-6). Uranium-235 shows a similar distribution to uranium-233/234. Wells with the highest concentration-activities are clustered in the Solar Ponds Area and downgradient towards North Walnut Creek.

Uranium-238 concentration-activities above the Tier II action level of 0.768 pCi/L have been found across RFETS (Figure 5-7). Wells with groundwater concentration-activities above the background benchmark are located in the Solar Ponds Area and to the north and south near the Site boundary. Other wells with groundwater activities-concentrations of uranium-238 near the background benchmark are clustered in the Solar Ponds Area and extend downgradient toward North Walnut Creek. Wells with groundwater concentration-activities above the action level but below the background benchmark are also located in the 881-Hillside Area, in the South Walnut Creek drainage, and near the Present Landfill.

In summary, Figures 5-5 through 5-7 show that locations having concentration-activities of uranium isotopes above the action levels are distributed across the Site in both background areas and in areas affected by Site activities. There are four areas with wells having groundwater concentration-activities above the Tier II action levels for the uranium isotopes (but rarely above the background benchmark): the Solar Ponds Area, South Walnut Creek drainage, the 881-Hillside Area, and the Present Landfill Area. In the following section Uranium-238/Uranium-235 atom ratios and Uranium-234/Uranium-238 activity ratios are calculated and will be used to discuss the likelihood that the uranium is anthropogenic or naturally occurring.

5.2.2 Use of U-238/U-235 Atom Ratios to Determine Origin of Uranium

The atom ratio of uranium-238 to uranium-235 in naturally occurring uranium is a constant of 137.8. This atom ratio can be used to separate the components of anthropogenic (i.e., enriched or depleted) uranium and naturally occurring uranium. Efurd et al. (1993) used the following equation to transform activities in pCi/L into atom ratios:

$$A = N * \lambda$$

where: A = activity, N = number of atoms of the isotope, λ = decay constant (0.693/half-life), λ for uranium-238 = 9.84375E-10, λ for uranium-235 = 1.55103E-10

Mean atom ratios were calculated for each well location with results above the background benchmark, using the mean activity-concentration from 1991 through 1996 (Table 5-5). The ratios vary from 54.5 to 251. Two background wells appear in Table 5-5 . The atom ration for well B205589 is 146 and 89.4 in well 10294. This wide range in ratios for these background wells may indicate that this method is not useful in determining the source of uranium in groundwater at RFETS. This may be due to variability in the analytical system that has not been accounted for in the calculation of the ratios or to differences in solubility of the two isotopes. See Section 3.6 for further discussion of atom ratios.

5.2.3 Use of U-234/U-238 Activity Ratios to Determine Origin of Uranium

The U-234/U-238 *activity* ratio (as opposed to the U-238/U-235 *atom* ratio) has also been used to distinguish between natural and anthropogenic uranium. Uranium-234 is a product of the uranium-238 decay chain and its abundance is determined by the abundance of uranium-238. Table 5-6 shows activity ratios for filtered uranium-238 and uranium-235 in groundwater calculated for locations with average activities above the background benchmark.

Table 5-5. Uranium Isotope Atom Ratios for Filtered Groundwater Locations Above Background.

Location	Mean U-238	U-238 N No. of Atoms	Mean U-235	U-235 N No. of Atoms	U-238 N/U-235 N
61093	39.2	2.52735E+12	0.991	1.00673E+10	251
07391	33.9	2.18753E+12	0.868	8.81958E+09	248
B305389	14.7	9.44340E+11	0.504	5.12306E+09	184
P208989	37.7	2.43117E+12	1.57	1.58979E+10	153
2689	76.9	4.96058E+12	3.33	3.37981E+10	147
B205589	84.3	5.43724E+12	3.66	3.71351E+10	146
B210389	49.9	3.21915E+12	2.19	2.22476E+10	145
4689	106	6.80838E+12	4.73	4.80406E+10	142
B208689	47.7	3.07674E+12	2.20	2.23232E+10	138
1786	28.5	1.83411E+12	1.32	1.34503E+10	136
P209889	28.9	1.86037E+12	1.35	1.37557E+10	135
P210289	41.2	2.65566E+12	1.94	1.97079E+10	135
B303089	115.	7.41443E+12	5.45	5.53651E+10	134
2886	95.6	6.16411E+12	4.59	4.65763E+10	132
B206589	20.5	1.32035E+12	1.01	1.02703E+10	129
06491	22.5	1.44775E+12	1.13	1.14438E+10	127
B208589	26.9	1.73476E+12	1.37	1.39615E+10	124
P209489	26.5	1.70989E+12	1.37	1.38923E+10	123
1586	15.4	9.93339E+11	0.833	8.46554E+09	117
35691	13.4	8.65134E+11	0.730	7.41511E+09	117
05393	66.4	4.28361E+12	3.64	3.69879E+10	116
37791	15.1	9.74289E+11	0.861	8.74291E+09	111
0586	23.4	1.50962E+12	1.35	1.36671E+10	111
10692	10.9	7.05630E+11	0.679	6.89277E+09	102
2187	18.8	1.20860E+12	1.17	1.18805E+10	101
B210489	21.7	1.39865E+12	1.36	1.38070E+10	101
05093	144	9.29110E+12	9.53	9.67992E+10	96.0
3086	63.9	4.12208E+12	4.31	4.38000E+10	94.1
2686	21.1	1.35808E+12	1.44	1.46603E+10	92.6
10294	31.0	1.99588E+12	2.20	2.23337E+10	89.4
01391	7.47	4.81547E+11	0.532	5.40920E+09	89.0
5287	23.4	1.50601E+12	1.73	1.76024E+10	85.6
37191	6.51	4.19733E+11	0.483	4.90637E+09	85.6
05193	90.4	5.82579E+12	10.5	1.06829E+11	54.5

Note: Bold locations are background wells.

The activity ratios of uranium-234 to uranium-238 are approximately 0.09 in depleted uranium, 1.06 in natural uranium, 5.74 in power-reactor fuel, and higher for weapons-grade uranium (EG&G, 1988). The U-234/U-238 activity ratio in for uranium in natural waters usually ranges from one to three, the higher activity of uranium-234 in natural waters appears to result from selective mobilization (Hess et al., 1985). Therefore, ratios that are above 3.0 or below 1.0 suggest the presence of artificially enriched or depleted uranium. The BGCR (DOE, 1993a) reported a range of 1.19 to 2.43 for ratios of uranium isotopes in filtered background groundwater, well within the expected range for natural waters. The current data shown in Table 5-6 have a range from 0.46 to 2.20. Only two wells have low activity ratios, Well 07391 located about 300 feet south of the 903 Pad and Well 61093 located near the Original Landfill. The variability in the analytical system that has not been accounted for in the calculation of the ratios and differences in solubility of the two isotopes due to Site-specific geochemical conditions may limit the usefulness of the activity ratios in determining the origin of the uranium in groundwater. Refer to Section 3.7 for a discussion of activity ratios.

Table 5-6. Uranium Isotope Activity Ratios for Filtered Groundwater Locations Above Background.

Location	Mean U-233/234	Mean U-238	234:238
05193	198	90.4	2.20
0586	39.5	23.4	1.69
B206589	33.1	20.5	1.62
B210389	80.9	49.9	1.62
P208989	59.1	37.7	1.57
3086	98.2	63.9	1.54
05093	220	144	1.53
B208689	72.9	47.7	1.53
B305389	22.1	14.7	1.51
4689	158	106	1.50
2886	141	95.6	1.47

Table 5-6 (continued)			
06491	32.5	22.5	1.45
B205589	121	84.3	1.43
2187	26.5	18.8	1.41
5287	32.7	23.4	1.40
P209889	40.0	28.9	1.39
10692	14.9	10.9	1.36
35691	18.0	13.4	1.34
37191	8.72	6.51	1.34
2686	28.0	21.1	1.33
1786	37.6	28.5	1.32
B208589	35.6	26.9	1.32
B210489	28.0	21.7	1.29
2689	95.1	76.9	1.24
05393	81.1	66.4	1.22
10294	37.3	31	1.21
P209489	31.8	26.5	1.20
P210289	49.3	41.2	1.20
1586	18.0	15.4	1.17
37791	17.7	15.1	1.17
B303089	135	115	1.17
01391	7.76	7.47	1.04
07391	16.0	33.9	0.47
61093	16.5	39.2	0.42

5.3 ACTINIDE TRNSPORT BY GROUNDWATER

Transport processes that potentially affect the movement of actinides in groundwater include mainly physical processes, such as detachment, entrainment and advective transport of colloids and particulates, filtration and settling of colloidal and particulates in saturated porous media, and geochemical processes, such as dissolution/precipitation, adsorption/desorption, and oxidation/reduction. Groundwater flowing through geologic materials with moderate to high hydraulic conductivities has the potential to carry both dissolved and finely divided suspended matter. Discharge of groundwater at seeps and into streams (gaining reaches) can result in actinide migration from groundwater to surface water.

Groundwater transport appears to be of most concern for uranium isotopes rather than americium or plutonium, due to their greater mobility in the groundwater environment of RFETS (Figures 5-2, 5-3, 5-5, 5-6, and 5,7). The reasons for this are discussed in Section 3. Areas of elevated uranium isotope concentration-activities occur in the Solar Ponds Area and down gradient, towards North Walnut Creek and in the 881 Hillside Area, upgradient of the SID and Woman Creek. Although most of the reported concentration-activities for uranium isotopes in these areas are below the current background benchmark values, the potential exists for groundwater uranium to be transported to surface water in these areas and to contribute to the exceedance of the surface water action level for uranium which is 10 pCi/L for total uranium isotopes.

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6.0 ACTINIDE DISTRIBUTION AND TRANSPORT IN SURFACE WATERS

This section provides a review of surface water actinide sampling data collected from 1990 through the present[1]. Past studies of actinide distribution and transport are also cited and discussed.

This review of data involving actinide transport in surface water is divided into the following categories:

- Actinide distribution in surface water by Site location;
- Actinide transport in surface water;
- Impact of watershed changes on actinide transport;
- Summary observations of actinide transport in surface water; and
- Detailed presentation of data, plots, and discussion (Appendix B).

Analyzing the distribution and mechanisms involved with transporting actinides in surface water is necessary for understanding the conditions required for such transport to occur. The RFCA specifies standards for actinide activities at specific surface water monitoring locations. The RFCA-driven Integrated Monitoring Plan (IMP) specifies analytes and sampling methodologies (detailed in Appendix B, Section B.1) for Site surface water monitoring locations. Increased understanding of actinide distribution and transport in surface water at RFETS will benefit the decision-making process for implementing control measures that could minimize surface water actinide transport and the resulting implications related to elevated actinide activity measured at RFCA surface water monitoring stations.

[1] The time frame that data was collected ranges from surface water monitoring station to station. The operational time frame for each station is listed in Table 6-2.

6.1 ANALYSIS OF ACTINIDE DISTRIBUTION IN SURFACE WATER

6.1.1 Background Levels of Actinides in RFETS Surface Water

As discussed in Section 4.1, plutonium and americium occur very sparingly, or not at all, in nature. However, plutonium and americium do occur in the environment due to fallout from atmospheric nuclear weapons tests and from the re-entry and burnup of a nuclear powered satellite in 1964.

The geology in the RFETS area and a generally alkaline and oxidizing environment in the near-subsurface support the presence of naturally-occurring dissolved uranium in background-quality surface water. The presence of plutonium or americium in surface water, in contrast, is theorized to result from surface water transport of suspended solids, derived from soils and sediments, that contain these actinides (as discussed above in Section 4.3).

Background surface water quality at RFETS was characterized utilizing 15 surface water monitoring locations as part of *the Final Background Geochemical Characterization Report* (EG&G 1993). A total of 1 station (SW107) is located in the Woman Creek drainage upstream of the Site and 4 stations (SW041, SW080, SW104 and SW127) are located within Woman Creek tributaries west or southwest of the IA. Surface water stations SW004, SW005, SW006, SW108, SW134, SW135, SW136 and SW137 are located along the Rock Creek drainage or within unnamed tributaries of Rock Creek. Station SW007 is situated in the McKay Ditch upgradient of any IHSSs, and SW130 is located on Smart Ditch in the south BZ, just east and downgradient of Rocky Flats Lake. Three of the above water monitoring stations (SW080, SW104 and SW108) sample seep flows, whereas, the other monitoring stations are in-stream locations. All of these monitoring stations are located outside of the general area where the IA or the 903 Pad and Lip Area drain and are assumed to have been unaffected by historical activities at RFETS.

Table 6-1 summarizes the results of total (i.e., unfiltered) sample analyses for actinide activity in background RFETS surface water. The mean activities for both plutonium and americium in surface water are also consistent with the activities measured in TSS (i.e., mean = 18,900 ug/L) and the sediments (means were 0.07, 0.17 and 1.48 pCi/g for Am-241, Pu-239/240, and Total Uranium, respectively), assuming that the sediment activities are representative of TSS levels. Uranium levels in surface water are also lower than those in background groundwater, consistent with the theory of overland flow diluting groundwater discharged to surface water.

Table 6-1. Summary of Background Surface Water Quality for Total Radionuclides

Radionuclide	# of Samples (n)	Mean Activity (pCi/L)
Americium - 241	106	0.00
Plutonium - 239,240	105	0.00
Uranium - Total	17	0.59

Source: EG&G (1993).

6.1.2 Actinide Levels at Surface Water Sampling Locations

Surface water runoff from the IA is directed into three main drainages and associated detention pond systems (Figure 6-1):

- North Walnut Creek (A-series ponds);
- South Walnut Creek (B-series ponds); and
- South Interceptor Ditch (SID) (Pond C-2).

The water quality is largely influenced by the sampling location (e.g., upstream versus downstream from a detention pond). For the purposes of this actinide transport analysis, the discussion of surface water was subdivided upstream-to-downstream as follows:

- IA runoff (surface water flowing within the IA fence);
- Detention Pond influent (downstream from the IA, but upstream from the ponds); and
- Detention Pond effluent (downstream from the ponds).

The monitoring stations located in each of these drainages are shown in Figure 6-1 and listed in Table 6-2. Sample results at each monitoring station are effected by the sampling methodology employed. Two distinct sample collection methods, storm-event and continuous flow-paced sampling (as specified by the RFCA Integrated Monitoring Plan), are utilized to monitor actinide activity of surface water at the Site. Storm-event samples, which reflect the quality of water in the "first-flush" of a precipitation event, typically yield higher actinide activity results than do continuous flow-paced samples that reflect the quality of all the water that flows past a particular sampling station. These sampling methods are described in further detail in Appendix B (Section B.1.3).

Table 6-2. Summary Information for Surface Water Sampling Locations

Station	Drainage	Location Description	Operation Period	Projects	Sample Types	Average Annual Yield (acre-feet)
Industrial Area Runoff Sample Locations						
GS27	SWC	ditch NW of Building 889	1995 - present	IM/IRA Tier II; IMP	Flow-paced Storm-Event	0.28
GS28	SWC	Ditch NE of Building 889	1995 - present	IM/IRA Tier II; RFCA Perf.	Flow-paced Storm-Event	1.13
GS21	SID	small culvert SE of Bldg. 664	1995 -1996	IM/IRA Tier II	Flow-paced Storm-Event	2.13
GS22	SID	outfall at SID of 400 Area culvert	1995 -1996	IM/IRA Tier II	Flow-paced Storm-Event	37.50
GS24	SID	small culvert S of Bldg. 881	1995 -1996	IM/IRA Tier II	Flow-paced Storm-Event	0.84
GS25	SID	ditch draining SE of Bldg. 881	1995 -1996	IM/IRA Tier II	Flow-paced Storm-Event	5.41
Detention Pond Influent Sample Locations						
SW093	NWC	N. Walnut Cr. Upstream from the A-1 bypass	1991 - present	Event-Related; IM/IRA Tier I; ALF	Flow-paced Storm-Event, Continuous	118.7
SW091	NWC	Gully NE of Solar Ponds tributary to N. Walnut Creek	1995 - present	IM/IRA Tier I; NSD	Flow-paced Storm-Event	1.38
SW022	SWC	Central Ave. Ditch at Inner East Fence	1995 - present	IM/IRA Tier I; NSD	Flow-paced Storm-Event	29.40
GS10	SWC	S. Walnut Creek upstream from the B-1 bypass	1991 - present	Event-Related; IM/IRA Tier I; NSD, ALF	Flow-paced Storm-Event, Continuous	85.40
SW027	SID	South Interceptor Ditch at Pond C-2	1991 - present	Event-Related; IM/IRA Tier I; NSD, ALF	Flow-paced Storm-Event, Continuous	32.80

Station	Drainage	Location Description	Operation Period	Projects	Sample Types	Average Annual Yield (acre-feet)
Detention Pond Effluent Sample Locations						
Pond A-4	NWC	Terminal pond in N. Walnut Ck.	N/A (see Note 2)	NPDES	Composited grabs during discharge	387 (See Notes)
Pond B-5	SWC	Terminal pond in S. Walnut Ck.	N/A (see Note 2)	NPDES	Composited grabs during discharge	258
Pond C-2	SID	Terminal pond in SID/Woman Ck.	N/A (see Note 2)	NPDES	Composited grabs during discharge	33

Notes:

1) All values are based on record from water year 1995 through March 1997 (if applicable) and are preliminary and subject to revision.

2) Sampling periods for this pond discharge data are: Pond A-4, 1/91 to 6/96; Pond B-5, 3/94 to 6/95; and Pond C-2, 3/92 to 6/95.

3) Definition of abbreviations: NWC: North Walnut Creek; SWC: South Walnut Creek; SID: South Interceptor Ditch; NPDES: National Pollutant Discharge Elimination System; IM/IRA: Industrial Area Interim Measures/Interim Remedial Action; IMP: RFCA Integrated Monitoring Plan; NSD: RFCA New Source Detection monitoring; ALF: RFCA Action Level Framework monitoring.

6.1.3 Actinide Sample Results by Location

Table 6-3 provides a summary of radionuclide activities measured at the various Site surface water sampling station locations (which are shown on Figure 6-1). This provides an insight into the relative magnitude of activities measured at various locations around the Site (i.e., IA runoff stations versus pond influent versus pond effluent).

Sections 6.2.3.1 and 6.2.3.2 present observations regarding actinide distribution in surface waters at the Site based on the data presented in Table 6-3.

Table 6-3 Radionuclide Activities by Surface Water Sample Location

Station	Drainage	Sample Type	# of samples (n)	Avg. Pu-239,-240 (pCi/L)	Avg. Am-241 (pCi/L)	Avg. Total Uranium (pCi/L)
Industrial Area Runoff Sample Locations						
GS27	SWC	Storm Only	13	24.98	9.06	1.47 (n = 12)
GS28	SWC	Storm Only	11	0.156	0.061	0.676
GS21	SID	Storm Only	10	0.033	0.023	0.801
GS22	SID	Storm Only	8	0.0128	0.0178	0.710
GS24	SID	Storm Only	11	0.0931	0.031	1.4811
GS25	SID	Storm Only	9	0.018	0.012	1.518
Detention Pond Influent Sample Locations						
SW093	NWC	Storm & Continuous	36	0.409	0.198	3.266
SW093	NWC	Storm Only	17	0.816	0.396	2.149
SW093	NWC	Continuous	19	0.044	0.020	4.265
SW091	NWC	Storm Only	8	0.498	0.515	4.771
GS10	SWC	Storm & Continuous	66	0.195	0.166 (n = 67)	2.336
GS10	SWC	Storm Only	48	0.228	0.200 (n = 49)	2.069
GS10	SWC	Continuous	17	0.112	0.075	2.975
SW022	SWC	Storm Only	16	0.187	0.075	0.958; (n = 15)
SW027	SID	Storm & Continuous	18	0.305	0.058 (n = 17)	2.859
SW027	SID	Storm Only	14	0.385	0.074 (n = 13)	3.247
SW027	SID	Continuous	4	0.022	0.005	1.502
Detention Pond Effluent Sample Locations						
Pond A-4	NWC	Compos. grabs	139	0.007	0.008	1.789
Pond B-5	SWC	Compos. grabs	9	0.022	0.011	2.272
Pond C-2	SID	Compos. grabs	9	0.100	0.017	2.797

Note: averages are calculated as arithmetic averages of individual carboy (sample container) results.

6.1.3.1 Plutonium and Americium

The following observations may be made from the Pu-239/Pu-240 and Am-241 activities measured at surface water monitoring locations.

General Characteristics

- At stations where both storm-event and continuous flow samples have been collected (stations SW093, GS10, SW027 - located at the influent to Ponds A-4, B-5, and C-2, respectively), storm event samples contain significantly higher plutonium and americium activities than continuous flow samples collected at the same location. This variation is consistent when plutonium and americium are preferentially associated with particulate matter in the water column.

- Radionuclide activities in detention pond influent may be 1 to 2 orders of magnitude higher than the activities associated with the detention pond effluent. This indicates that the settling of particulate matter occurring in the ponds removes radionuclides from the water column[2].

Location-Specific Characteristics

- Plutonium and americium activities measured at IA runoff station GS27 during storm events are the highest measured at any automated monitoring location; a maximum value of 90 pCi/L was measured on June 28, 1997. Initially, a significant source upgradient of GS27 was suspected, however, surveys and soil sampling did not indicate the presence of a 'hot spot' or significant source.

[2] Pond C-2 is the exception; effluent activities from this pond are skewed higher by samples collected in spring 1995 as noted in Section 6.1.3.1.

- By comparing the mean plutonium activities for storm samples at IA runoff station GS27 and pond influent station SW022 (coupled with each location's corresponding annual surface-water yield), suggests that the GS27 sub-drainage may be contributing a significant portion of the plutonium load to SW022 (and hence to the South Walnut Creek drainage).

- SW022 has concentration activities of similar magnitude as GS10, and represents approximately 34% of the surface water runoff entering South Walnut Creek from the IA. Although SW022 measures runoff from the portion of the Site associated with uranium, it still represents a significant portion of the total actinide load, inclusive of plutonium and americium, to South Walnut Creek.

- Although station SW091 (Pond A-4 influent) has concentration activities similar to the other Pond A-4 influent location (SW093), SW091 represents only 1% of the surface water entering North Walnut Creek from the IA; and therefore comprises only a small portion of the total actinide load to North Walnut Creek.

- Comparing the mean plutonium activities for stormwater samples at IA runoff stations GS21, GS22, GS24, and GS25 (sub-basin monitoring upstream from station SW027) with station SW027 (Pond C-2 influent), coupled with each location's corresponding annual surface-water yield, suggests that none of these IA locations is contributing a significant portion of the plutonium load to SW027. This suggests that the primary source for the activity measured at SW027 probably originates in areas (downstream of stations GS21, GS22, GS24, and GS25) that are affected by contamination from the 903 Pad Lip Area.

- Although Pond C-2 generally shows higher plutonium activities than Ponds B-5 and A-4, station SW027 (influent to Pond C-2) has lower average plutonium activities for continuous samples than do the stations that monitor the influent to Ponds A-4 and B-5 (SW093 and GS10, respectively).

The difference in the water quality for Pond C-2 compared to A-4 and B-5 may be attributable to several items:

◊ Water from Ponds A-4 and B-5 is diluted by WWTP effluent;
◊ Pond C-2 may receive loading only during very large precipitation events which result in significant overland flow from contaminated areas near the 903 Pad; and
◊ Other biological, physio-chemical, limnological, or management differences for Pond C-2 may result in resuspension of contaminants.

6.1.3.2 Uranium

Location-Specific Characteristics

- Total uranium increased significantly at SW093 (Pond A-4 influent) for continuous samples compared to storm events. This result suggests that uranium may be preferentially associated with baseflow, especially groundwater seeps. This is consistent when storm events occur, overland runoff causes dilution of the uranium contained in the baseflow and, hence, the storm event samples contain lower total uranium activity than the continuous flow samples. The proximity of SW093 to the Solar Ponds could also be influencing the uranium concentration in surface water flow.

Measurably less uranium is observed at SW027 (Pond C-2 influent) for continuous samples compared to storm events. This suggests that uranium may be preferentially associated with storm runoff, or that the source of baseflow may be low in uranium, or that baseflow from natural sources is minimal at this location (which has been confirmed by flow monitoring).

6.2 ANALYSIS OF ACTINIDE TRANSPORT IN SURFACE WATER

6.2.1 Relationships between Radionuclides, Suspended Solids, and Flow

A study of the behavior of radionuclides in surficial soils suggests that relationships exist between radionuclide activity, TSS, and surface water flow rate. Plutonium and americium have a tendency to form associations with particulate materials; therefore, their transport is expected to correlate with the transport of the material with which they are associated. Suspension of particulate material by raindrop impact and/or streamflow might be expected to facilitate transport of the associated radionuclides. Consequently, a dynamic relationship between TSS concentration and the radionuclide activity in the surface water could be anticipated. The relationship would be dynamic because the state of drainages at the Site changes as contamination is removed, isolated, or exposed.

Solids mobilize, and thus, TSS can be related to flow rate if the particulate matter is suspended by runoff. The amount of TSS will vary depending on the magnitude of the flow. Generally, a more intense precipitation event will generate higher flow rates and is expected to suspend more solids by various transport mechanisms, including ditch and wetland scouring, sheet flow on bare soils, and raindrop impact.

Consequently, if a relationship between radionuclide activity and TSS exists for a given location, then radionuclide concentration-activity may be correlated with flow rate as well. Although these relationships might be anticipated for most sampling locations, determination of whether this relationship exists may be difficult to assess for several reasons:

- A TSS (mg/L) to radionuclide (pCi/L) relationship assumes that the activity is proportional to the mass of solids independent of available surface area or particle composition. However, radionuclide association involves the physiochemical properties of the particles themselves, and is more complex than a simple pCi/g relationship.

- Source areas in any particular drainage may have unique physiochemical characteristics and contamination levels may vary within a drainage making the water quality characteristics of runoff from a sub-drainage would be unique. When precipitation events do not occur uniformly over an area (especially for large drainages), the water quality characteristics measured at a monitoring location will depend on the origination of that runoff. In fact, there may be several, or many, concurrent relationships that could be established for a given location.

- Since a given drainage is continually changing, either through natural erosion or anthropogenically through decontamination and decommissioning (D&D) or construction activities, there may not be time to collect sufficient information to determine one relationship before it is superseded by another.

6.2.2 Site-Specific Actinide Relationships with Suspended Solids and Flow

In order to understand the site-specific relationships between the actinides, the relationship between measured activities, TSS, and flow were evaluated for each of the surface water sampling stations. The analyses that were performed included evaluating Plutonium activity versus flow, Americium activity versus flow, Total uranium activity versus flow, Plutonium activity versus TSS, andAmericium activity versus TSS.

The results of these evaluations are summarized in Table 6-4. A detailed discussion, including plots used for the above analyses is located in Appendix B.

Table 6-4. Summary of Regressions between Actinides, Flow, and Suspended Solids.

Station	Drainage	Sample Type	# of samples (n)	Pu vs. flow trend	Am vs. Flow trend	Tot U vs. flow trend	Pu/Am vs. TSS trend	Correlation Notes / (Implications)
Industrial Area Runoff Sample Locations								
GS27	SWC	Storm Only	13	(+)	(+)	none	(+)	Am vs. TSS: $R^2 = 0.89$ (Minimizing erosion could minimize rad transport)
GS28	SWC	Storm Only	11	none	none	none	<u>(+)</u>	Pu vs. TSS: $R^2 = 0.92$ (Minimizing erosion could minimize rad transport)
GS21	SID	Storm Only	10	(+)	(+)	none	none	low activity in samples
GS22	SID	Storm Only	8	(+)	(+)	none	none	low activity in samples
GS24	SID	Storm Only	11	(+)	(+)	none	none	low activity in samples
GS25	SID	Storm Only	9	(+)	(+)	none	none	low activity in samples
Detention Pond Influent Sample Location								
SW093	NWC	Storm & Continuous	36	none	none	(-)	(+)	(Tot. U contained in baseflow, diluted by stormwater)
SW091	NWC	Storm Only	8	<u>(+)</u>	<u>(+)</u>	none	<u>(+)</u>	Pu vs. flow: $R^2 = 0.96$ Pu vs. TSS: $R^2 = 0.92$ (Minimizing erosion could minimize rad transport)
GS10	SWC	Storm Only	48	none	none	none	(+)	Pu vs. TSS: $R^2 = 0.89$
SW022	SWC	Storm Only	16	none	none	none	(+)	(Large basin variability possible cause for weak correlations).
SW027	SID	Continuous	4	(+)	(+)	(-)	none	(Low TSS at SW027 makes TSS trending difficult.)

Notes: (1) Activities are measured as pCi/L; Flow is measured as cfs; TSS is measured as mg/L.
(2) Where trends from the regressions, whether positive or negative, were observed, they are noted with (+) or (-) signs, respectively. (3) When the regression R^2 value is greater than 0.90, the trend is noted with (+) or (-) symbols underlined and the R^2 value is listed in the Correlation Notes column of the table. (4) Where trends from the regressions, whether positive or negative, were observed, they are noted with (+) or (-) signs, respectively. When the regression R^2 value is greater than 0.90, the trend is noted with (+) or (-) signs underlined and the R^2 value is listed in the Correlation Notes column of the table. Potential implications of these relationships are also noted in the last column. A detailed discussion of these relationships is provided in Appendix B and summarized according to each sampling location.

6.3 IMPACT OF WATERSHED CHANGES ON ACTINIDE TRANSPORT

Two separate monitoring locations, GS27 (IA runoff) and SW027 (influent to Pond C-2), demonstrate how changes in the watershed impact water quality. Monitoring results from these locations reflect the challenge in collecting an adequate number of samples at variable flow rates once watershed improvements have been implemented in order to properly assess whether or not the improvements are reducing concentration-activity in runoff for both high and low flows.

6.3.1 Impact of Watershed Improvements at GS27

Station GS27 is located in a small basin, which drains less than 1 acre. Samples were collected before, during, and after watershed improvements have occurred within the basin. Station GS27 was installed to monitor for possible impacts of the D&D at Building 889 (completed in July 1996). The watershed improvements implemented in the basin included:

- Removing and drumming sediments, measured to contain 5 to 6 pCi/g of plutonium, accumulated on the asphalt south of Building 884 (completed July 1996); and
- Applying TopSeal® on the exposed dirt areas south of Building 884 (completed October 1996).

The majority of post-improvement samples were collected at low flow rates. Although data indicate low or lower actinide activities for a given flow, than prior to the improvements, it is impossible to extrapolate this data to define the impact on water quality of the control measures when higher flows occur. Station GS27 collects samples when a higher flow rate does occur. A plot of the GS27 data is presented in Appendix B (Section B.3.3.1).

6.3.2 Impact of Watershed Improvements on SW027

Sample results indicate a trend toward reduced plutonium and americium activity to flow ratios at SW027 since improvements were first implemented in this basin. A dirt road running south down the hill from the 903 Pad, toward Pond C-1, was revegetated during the summer of 1996 and treated with SoilGuard®. In addition, dirt roads encircling the 903 Pad were treated with TopSeal® during the past year. However, it should be noted that the sampling protocol at station SW027 changed from storm-event sampling to continuous flow-paced sampling as a result of RFCA requirements, in the midst of the improvements being implemented. Results of storm-event samples also indicate reduced radionuclide loading following the implementation of improvement measures. A plot of the SW027 data is presented in Appendix B (Section B.3.3.2).

6.4 SUMMARY OBSERVATIONS FOR ACTINIDE TRANSPORT IN SURFACE WATER

6.4.1 Uranium Transport in Surface Water

Surface water data from monitoring locations with baseflow near the Solar Ponds suggest that, as the surface water flow rate increases due to storm events, uranium activity decreases with dilution of baseflow. This trend is evident in the results from gaging station SW093 downgradient from the Solar Ponds. This phenomenon may be due to groundwater, which supplies the baseflow and is the primary source for uranium observed in the surface water. This finding is further supported by data from monitoring locations with ephemeral flow which exhibit no significant relationship between total uranium and flow rate. At stations with baseflow, the primary mechanism for uranium contamination of surface water may not be mobilization of particle-bound nuclides by storm events, but transport via groundwater supply of baseflow.

Uranium in surface water drainages is associated with baseflow in areas that drain the solar ponds (SW093, GS10), but appears to be associated with storm runoff in the areas south of Building 881 and the Original Landfill (monitored by SW027), where there is known surface uranium contamination. Total uranium activity is similar for the effluent from all three terminal detention ponds (Ponds A-4, B-5, and C-2). In North Walnut Creek, Pond A-4 (1.8 pCi/L) contains roughly one fourth the total uranium activity of the continuous flow for SW093, (4.3 pCi/L) which is located below the Solar Ponds. In South Walnut Creek, Pond B-5 (2.3 pCi/L) total uranium activity is slightly lower than the continuous flow sampled at GS10 (3 pCi/L). In the SID, Pond C-2 (2.8 pCi/L total uranium) contains slightly lower total uranium than is recorded for SW027 (3.2 pCi/L).

6.4.2 Plutonium and Americium Transport in Surface Water

6.4.2.1 General Plutonium and Americium Transport Mechanisms

Plutonium and americium transport is related to both TSS and flow rate. In general, sampling sites in small drainages provide more distinct, positive correlations compared to sites located in larger basins. The correlation is also stronger in drainages that collect runoff from areas with widespread, surface radionuclide contamination. Results from station GS10, a large basin capturing runoff from roughly two thirds of the IA, represent the exception to this observation by exhibiting a strong correlation between plutonium/ americium activity and TSS.

A positive correlation is observed between plutonium and americium concentration-activity and flow rate across the Site. As with the plutonium/americium relationship to TSS, the plutonium/americium correlation with flow is markedly better for smaller drainages. Again, this may reflect diminished contaminant level and rainfall variability inherent in smaller basin areas.

The positive correlations of concentration-activity with both TSS and flow suggests that transport of plutonium and americium is facilitated by dislocation and transport of suspended particles whose suspension is a function of flow rate and precipitation intensity. Despite mobilization of plutonium and americium detected during storm-events in storm event samples, pond effluent sampling indicates the pond system performs well to attenuate and settle contaminants in storm water prior to discharge offsite. Contaminant levels measured in storm water flowing from the ponds are typically decreased at least 10-fold from that of influent levels.

6.4.2.2 Location-Specific Plutonium and Americium Transport

North Walnut Creek at SW093 - This station has continuous baseflow, but has relatively low levels of plutonium and americium in the continuous-flow samples. However, SW093 storm-event samples (0.816 pCi/L Pu) have higher plutonium and americium concentration-activities than at locations influent to Ponds B-5 and C-2, GS10 (0.228 pCi/L Pu) or SW027(0.385 pCi/L Pu), respectively. SW093 collects water draining from IHSS 150.8, an area of surface contamination containing slightly elevated plutonium and americium contamination, as shown in Figures 4-1 and 4-2. Stormwater flushes this area and drains into a drop box. This storm flushing across the IHSS and through the sediments accumulated in the drop box is suspected of causing an increase in plutonium and americium loading during storm events. SW093 may also collect drainage from east of Building 771.

South Walnut Creek at GS10 - This station has continuous baseflow, with comparatively high levels of plutonium and americium activities. The plutonium and americium activities for continuous flow samples at GS10 (0.112 pCi/L Pu) are about 2 to 3 times greater than those for SW093 (North Walnut Creek, 0.044 pCi/L Pu) and SW027 (South Walnut Creek, 0.022 pCi/L Pu).

SW027 and Pond C-2 - Water flowing from the southern portion of the IA is collected in the SID, flows past station SW027, and into Pond C-2. Pond C-2 also collects water from the area immediately surrounding the pond, which includes areas downwind of the

903 Pad with surficial plutonium and americium soil contamination (Figures 4-1 and 4-2). The average plutonium activity for continuous flow sampling at SW027 (0.022 pCi/L) is less than the average plutonium activity in the Pond C-2 discharges (0.100 pCi/L). It should be noted that the continuous flow samples at SW027 have been collected only since October 1, 1996 (per RFCA IMP), whereas the Pond C-2 discharge data dates back to March 1992 and are skewed by high activities measured during the spring of 1995 when high runoff forced direct offsite discharges of Pond C-2.

The loading in Pond C-2 is from both the flow at SW027 and from water flowing into Pond C-2 from the basin immediately surrounding the pond. The Pond C-2 effluent data obviously does not distinguish these two contaminant loading pathways, although it the area surrounding Pond C-2 (that is, water not flowing from the SID) may provide a source of plutonium activity detected in Pond C-2.

6.5 REFERENCES

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7.0 ACTINIDE DISTRIBUTION AND TRANSPORT THROUGH AIRBORNE RESUSPENSION

The Site has been a source of airborne actinides throughout its history. The largest contributors are building ventilation systems and resuspension of contaminated soils. Building ventilation systems are sources of actinide deposition to the environment. Resuspension, however, is a mechanism for transport of actinides that are already in the environment. Airborne migration of actinides in the environment around the Site is primarily due to soil resuspension (DOE, 1995). Movement can be caused by natural processes (resuspension in a natural ecosystem caused by high winds, or by a combination of rain splash and wind movement of vegetation) or by a combination of artificial and natural processes (transport by wind of actinide-contaminated soil that is disturbed by earth-moving activities) (DOE, 1995).

Through these transport mechanisms, actinide and non-actinide particles are lifted from the contaminated surface and carried through the air. Resuspension, dispersion, and deposition of actinides in the environment is highly dependent on the physical and chemical form of the actinides. For example, the size of the particles affects their potential to be resuspended, and the chemical form of the actinide affects its potential to attach to other particles.

Measurements of plutonium in the ambient air have been routinely conducted at the Site for over twenty years using medium-volume ambient air particulate samplers. These samplers have been operated continuously on the Site, at the Site perimeter, and in several nearby communities. Not surprisingly, trends within the ambient air data show higher concentrations of plutonium near the contamination sources and decreasing concentrations with increasing distance from the sources (see Figure 7-1; based on data in Calendar Year 1992 Annual Report). This trend applies whether the source is a building, a remediation activity, or an area of contaminated soil. It is interesting to note, however, that simple modeling to account for airborne concentrations of plutonium activity at a sampling location near the Site perimeter suggests that as much as 30% of that activity is contributed by resuspended material near the sampler and not from the more highly contaminated, but distant source near the 903 Pad and Lip Area. The existing sampling network is shown in Figure 7-2.

Resuspension has not always been the majority contribution to plutonium in the ambient air around the Site. When the Site was producing triggers, plutonium from the building ventilation systems contributed a significant fraction of airborne plutonium and easily exceeded the resuspension component. Figure 7-3 shows the historical trend in plutonium concentration at a sampler (S-007) located just southeast of the 903 Pad. Cleanup activities, which can potentially contribute significantly to measured emissions from the Site, can also mask the contribution from the natural resuspension processes. It is important to note that ambient concentrations at the Site perimeter under these scenarios have been at least several orders of magnitude under the Clean Air Act standard.

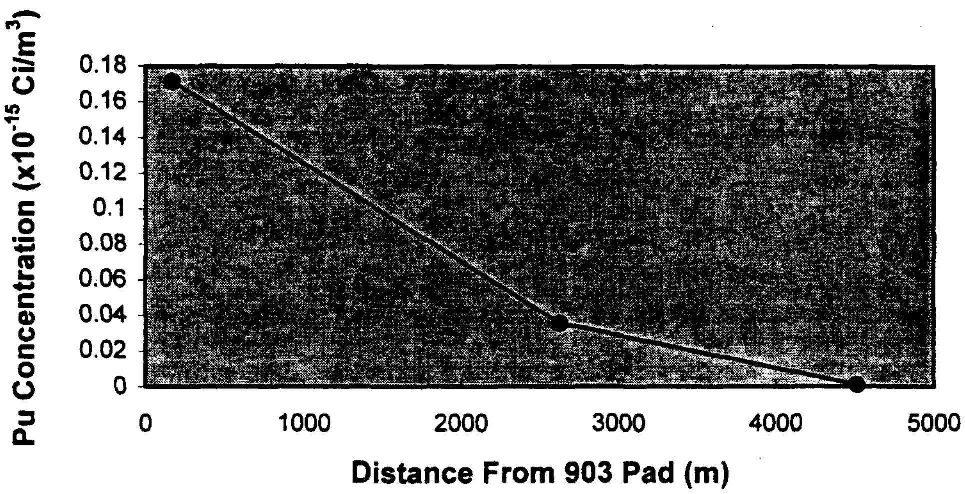

Figure 7-1. Plutonium Air Concentration vs. Distance from 903 Pad ('92 Data)

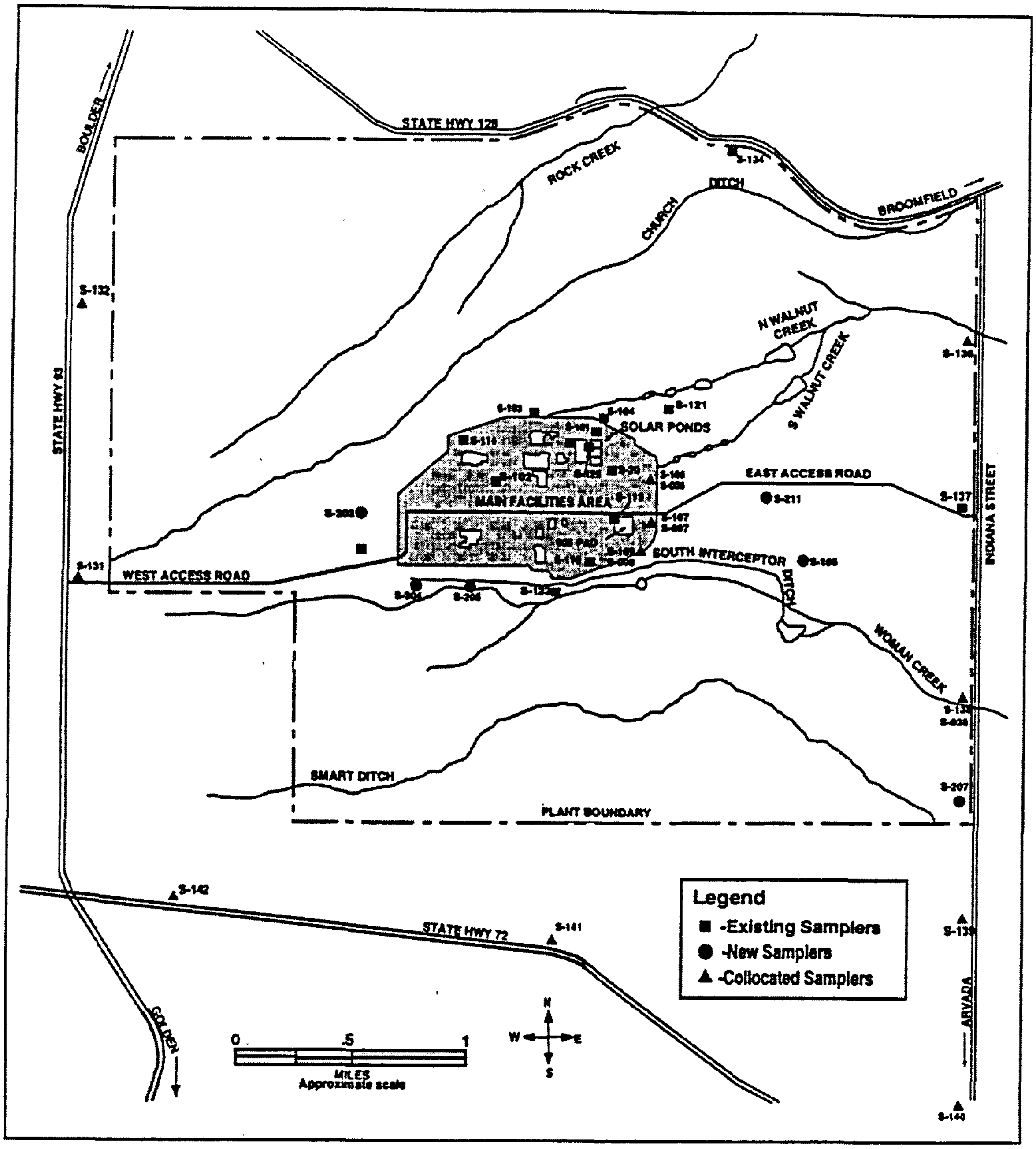

Figure 7-2. RAAMP Sampler Locations

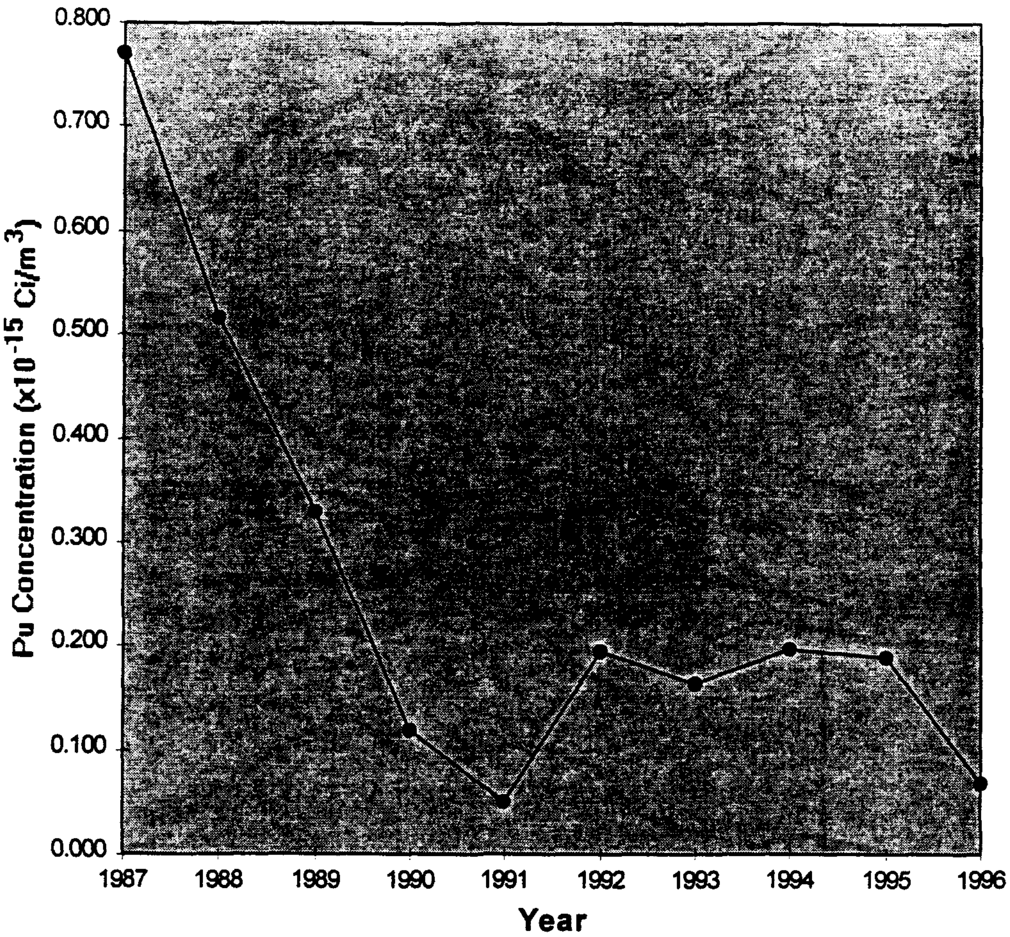

Figure 7-3. Annual Mean Plutonium Air Concentrations at S-007

7.1 Source Summary

The migration of actinides already in the environment through the air pathway is contingent on the actinides being available for entrainment and dispersion in the ambient air. The major source of resuspendable actinide material at the Site is the 903 Pad and Lip Area. The 903 Drum Storage Area was contaminated with plutonium-laden cutting oil stored in metal drums which, over time, leaked onto the soil beneath the drums. Removal of the drums in the late 1960's and associated cleanup activities in the early 1970's allowed the contaminated soil to disperse to the east and south of the 903 Pad Area (DOE, 1986). The Storage Area itself is now covered with asphalt, and is no longer a source of resuspendable plutonium; however, the initial spread of plutonium-contaminated soil prior to the installation of the asphalt pad, which now covers the area, resulted in a plume of plutonium in the surface soils extending from the pad to the east and east-southeast. The plume decreases in concentration from approximately 1,000 pCi/g just east of the 903 Pad to well under 1 pCi/g at the eastern boundary of the Site (DOE, 1994).

Because the Site measures plutonium in the ambient air, sources that contribute to the concentrations measured in the sampling network are not distinguishable directly. Through 1989 the Site was in production, and the plutonium from the building effluent systems was the major contributor to the plutonium in the ambient air. Resuspension from contaminated soil areas was a source of plutonium during this time, but the contribution was not directly quantifiable due to the effluent source contribution.

From 1989 through 1995, the Site activities included planning for cleanup, and D&D of Site structures with little actual production-type activity. During this period, Site airborne emissions decreased, and resuspension from the contaminated soils contributed the majority of the plutonium captured in the air samplers. In 1995, cleanup of contaminated soils, waste disposal areas, and buildings was initiated, and these project-specific emissions became measurable contributors of plutonium to the air, once again obscuring to some extent the contribution from contaminated area emissions (DOE, 1996). If new analyses were performed to better quantify the natural transport processes, the best data available for the quantification of the natural movement of actinides in air appears to be from 1990 to 1995.

7.2 Resuspension and Dispersion Mechanisms

Research on particulate resuspension took place for over 10 years at the Site, beginning in the late 1970s. The Site offers a unique opportunity to study resuspension. Most dust resuspension studies have focused on resuspension from earth moving activities, including piles of dirt exposed to the wind. Because the area contaminated by the 903 Pad Area emissions is covered with vegetation, the resuspension rate from the soil is orders of magnitude less than that observed from earth moving activities on exposed soil.

A Site-specific study (DOE, 1995) has suggested that resuspension at the Site does not occur solely from surface soils at high wind speeds through saltation, as in a typical resuspension scenario, but much of resuspension may occur instead from vegetated surfaces, and may occur at much lower wind speeds than are typically associated with resuspension. This study also suggests that the vegetated cover receives the plutonium through rain splash. The splash deposits fine particulates on the surface of plants where they are available for resuspension at very low wind speeds. The rain splash resuspension mechanism may explain the "chronic" year-round, low-level ambient air plutonium concentrations observed at the Site from 1990 to 1995.

Plutonium is a very dense element, giving small plutonium particles aerodynamic characteristics the same as those of a much larger soil particles. In other words, plutonium particles that could be typically resuspended and held aloft by the ambient air like soil particles have the activity of the smaller high density particle. Fine plutonium particles may also be attached physically or chemically to soil particles, resulting in less radioactive particles that are transported in the same manner as soil. The resuspended material from the 903 Pad Area is likely to consist of such particles along with other uncontaminated soil material.

Data have been collected near the 903 Pad Area that indicate the typical sizes of ambient airborne radioactive particles. The data show that the amount of plutonium collected is generally proportional to the total mass collected, and is distributed uniformly in the mass distribution across size ranges from sub-micron to greater than ten microns. The study was completed under conditions when no major cleanup activities were in progress, and the Site was not in production. Consequently, the size fractionation data available from the study are characteristic of resuspended material from the 903 Pad Area (DOE, 1995).

Other data collected specifically for cleanup activities by new Radioactive Ambient Air Monitoring Program (RAAMP) samplers could be used in a limited capacity to determine size fractionation of resuspended material from earth-moving activities. Data have been taken from samplers at a range of distances from cleanup activities, and have been fractionated at approximately 10 micrometers aerodynamic diameter.

7.3 Sampling Summary

The RAAMP samplers in use during most of the 1990 to 1995 time frame were Site-designed medium volume air samplers. All samplers were located within the typical adult breathing zone (about 5 feet from the ground), operated continuously at a flow of 25 cubic feet per minute (cfm), and collected total suspended particulates (TSP). Samples were collected on an 8 x 10 inch fiberglass filter, which is rated to be 99.97% efficient for conditions routinely encountered in ambient air sampling. Filters were collected biweekly from all samplers and composited for monthly analysis. Isotopic analysis was then performed for plutonium-239. These samplers are known as the "old" RAAMP samplers. New size-fractionating RAAMP samplers that operate at 40 cfm and collect material on two substrates were installed in 1995. Particles larger than approximately 10 micrometers are collected on an oiled substrate, while particles smaller than 10 micrometers are collected on a standard 8-by 10-inch fiberglass filter.

A total of 43 samplers were used in the RAAMP network: 25 were located inside the Site boundary, 14 were at the Site perimeter, and 14 were in the communities adjacent to the Site. Typically, many of the samplers collected such small amounts of radioactive material that the activity was below quantifiable detection limits.

Several of these samplers were located near the 903 Pad Area: 3 samplers were located at the east end of the 903 Pad; 3 were located east of the 903 Pad Area along a several-mile stretch of the Site boundary; and several other samplers were located well to the east of the Site boundary. Those samplers outside the Site boundary typically do not yield data above quantifiable detection limits.

The samplers at the 903 Pad historically showed results above the quantifiable detection limits, while the samplers at the Site boundary only occasionally yield data above those limits.

7.4 REFERENCES

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DOE, 1994, Radionuclide Air Emissions Annual Report, Calendar Year 1994, Rocky Flats Environmental Technology Site.

DOE, 1995, Radionuclide Air Emissions Annual Report, Calendar Year 1995, Rocky Flats Environmental Technology Site, pp. 4-23.

DOE, 1996, Radionuclide Air Emissions Annual Report, Calendar Year 1996, Rocky Flats Environmental Technology Site.

DOE, 1996a, Action Levels for Radionuclides in Soils for the Rocky Flats Cleanup Agreement. Rocky Flats Environmental Technology Site, Golden, CO. October, 1996.

8.0 CONCEPTUAL MODEL OF ACTINIDE TRANSPORT AT RFETS

8.1 CONCEPTUAL MODEL

In an environmental investigation and remediation context, conceptual models are developed to understand relationships between a site's physical and chemical characteristics.

Conceptual models are used to establish the relationships between surface and subsurface geology and hydrology, meteorology, contaminant sources, contaminant types, and contaminant fate and transport (i.e., distribution processes in soil, sediment, air, groundwater, and surface water). The development of a conceptual model is an iterative process whereby the available data are compiled and integrated into an overall understanding of the site. As the conceptual model is developed, data deficiencies or areas of uncertainty may become apparent. Therefore, completion of the conceptual model may require collection of additional data and integration of the new data into the model to fill the data deficiencies or to address specific areas of uncertainty.

The transport of actinides includes both chemical and physical processes. Physical transport is the movement of the media that contains the actinides (i.e., soil or water). Chemical transport is the transfer of actinides in solution or from one physical form to another (e.g. the chemical transfer of actinides from soil particles to solution in groundwater). The processes vary among different sites depending on various environmental factors. When the site-specific transport mechanisms are understood and quantified to the extent possible, specific remedial actions may be evaluated, decisions on remediation design may be made, and analysis of the protectiveness of surface water may be completed. Near-term actions can be completed based on conceptual model predictions, which also provide the basis for evaluation of moderate to long-term actions.

A preliminary conceptual model of actinide distribution and transport at the Site, as summarized here, presents our current level of understanding of relationships between soil types, actinide distribution, hydrogeology, and the potential effects of actinides on surface water and air quality described in the conceptual model distributed to Stakeholders on June 6, 1997. Data deficiencies and areas of uncertainty have been identified. The conceptual model of actinide transport at RFETS is a living document that will be revised and formally updated as new data are obtained, which is the primary focus of the actinide migration study program during the next two fiscal years (FY98 and FY99). In addition, data that are currently available from sitewide and project-specific monitoring will continue to be compiled, reviewed and reanalyzed to confirm, enhance, or modify the current conceptual model.

The conceptual model of actinide fate and transport has been constructed based on preliminary investigations at RFETS, studies conducted at other DOE sites, universities, and a general knowledge of RFETS geology, hydrology, and meteorology. The conceptual model identifies the various pathways for the migration of actinides at the Site, as illustrated in Figure 8-1. Actinides in the various media exist in one of two phases: a solid/amorphous phase (particulate, colloidal) or a dissolved phase. The particulate/ amorphous phases consists of actinides contained within or adsorbed to soil or sediment particles that may be suspended in surface water, groundwater, or air, where the actinides are subject to mechanical (physical) movement and redistribution.

The dissolved phase contains the actinides in solution where migration is by both chemical (e.g. diffusion) and physical means (i.e., water movement). Figure 8-1 illustrates the environmental media that contain actinides and the transport pathways, where "R" denotes the various rates of transport and the subscripts designate the transfer-specific processes.

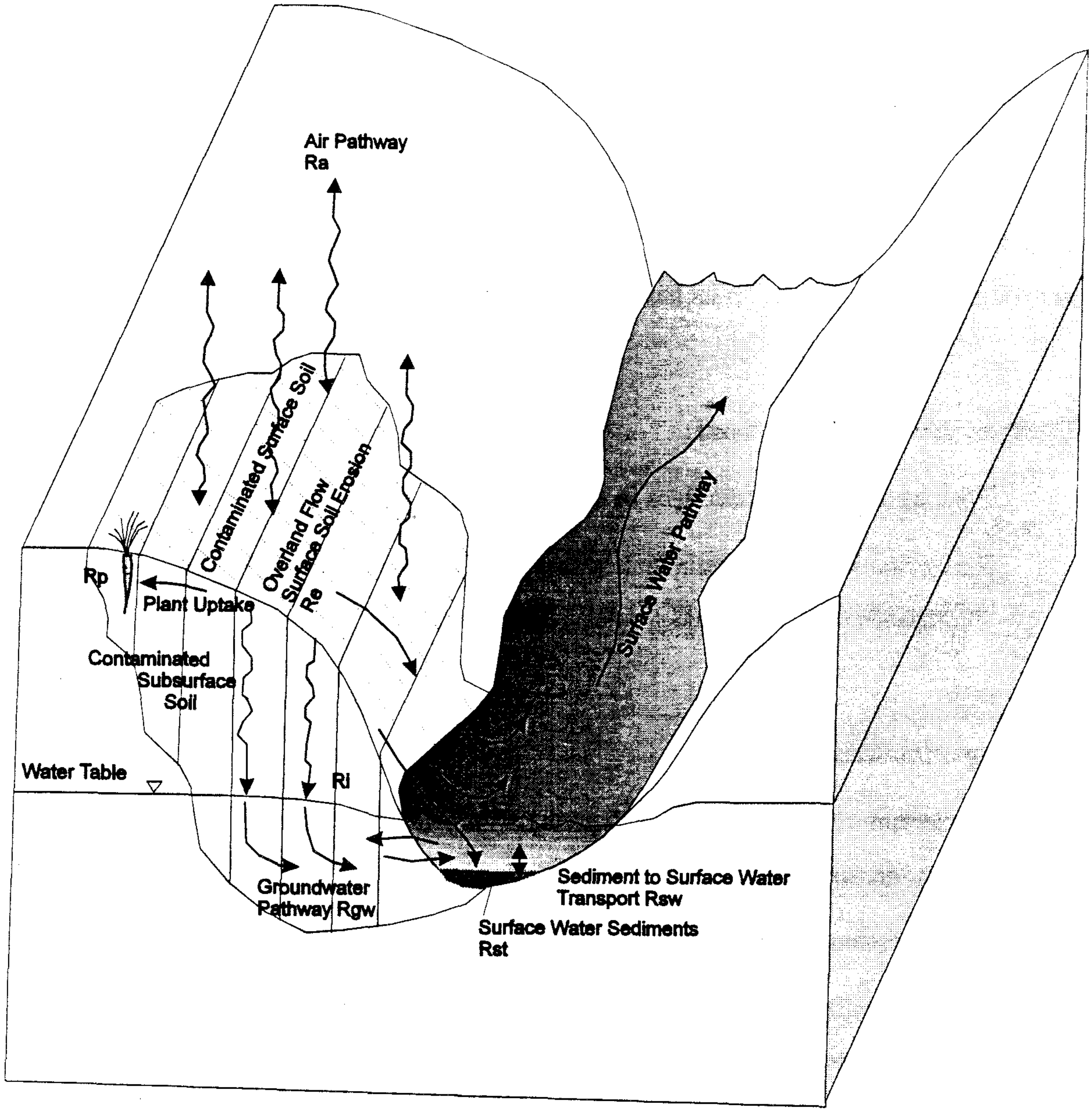

Figure 8-1. Preliminary Conceptual Model of Potential Actinide Transport Pathways

R = rate of actinide transport, subscripts indicate transport mechanism
Ra = air
Re = soil erosion
Rgw = groundwater
Ri = infiltration
Rsw = sediments to surface water and surface water to sediments
Rst = sediment transport
Rp = plant uptake

The migration pathways may be further divided according to processes that cause the transport or redistribution of actinides in each medium (soil, sediment, air, groundwater, and surface water). Transport processes contain both areal and vertical components. Most transport processes for actinides in soils can be described in terms of the agent causing the movement (e.g. air, surface water, groundwater). The primary transport processes controlling actinide migration include:

Transport due to flora and fauna:

- Plant uptake of radionuclides in soil; and
- Redistribution of contamination within the soil column due to burrowing fauna (bioturbation) or flora root growth (macro-channels).

Air transport processes include:

- Dispersion of point sources originating from site processes or building exhausts during site operations;
- Wind erosion of soils and transport of particulates downwind;
- Particulates that become airborne due to on-site activities (e.g., excavation, regrading, structure demolition); and
- The resuspension by wind of splash deposited particulates.

Surface water transport processes include:

- Erosion by overland flow of water transporting sediments to downslope locations;
- Dissolution of contaminants into overland flow and subsequent partitioning back onto soils or transport to drainages at downslope locations;
- Rain splash deposition of particulates onto flora or structure surfaces.

- Dissolution of actinides from contaminated sediments into surface water;
- Resuspension of particulates or sediments previously deposited in drainages;
- Movement of colloidal/amorphous phases as part of each of the above surface water processes; and
- The infiltration to groundwater of contaminated surface water (with actinides either in colloidal/amorphous phases or solution).

Groundwater transport processes include:

- Dissolution of contaminants into groundwater and subsequent partitioning back onto soils or transport to surface water at downgradient locations;
- The suspension, transport and deposition of colloidal particulates in infiltrating water. Chemical interactions are also important for these phases. The behavior of the colloidal/amorphous phases may be more that of large aqueous species than that of small soil particles; and
- Discharge to surface water of contaminated groundwater bearing actinides in solution or as suspended solids.

The above processes will vary based on a variety of factors. Processes requiring actinide dissolution are relatively insignificant for either plutonium or americium due to limited aqueous solubility, whereas, uranium is soluble in water and groundwater transport processes can be significant. Site location is important because it determines the type of contaminants that are present and the distribution within the various media. For example, on the north side of North Walnut Creek, there is little surface soil actinide contamination and soil erosion processes will not cause significant transport of actinides in this area. The conceptual model integrates and focuses our approach to how actinides migrate at RFETS, making it possible to refine our approach according to the portion of the Site that is being considered.

Actinide transport is most appropriately evaluated along the primary surface water pathways at RFETS that have actinide contamination including: the IA; the Woman Creek drainage; the South Walnut Creek drainage; and the North Walnut Creek drainage. Walnut Creek is the drainage basin for the majority of the IA. Runoff from the northern portion of the IA flows into North Walnut Creek. Runoff from the central portion of the IA flows into South Walnut Creek. Surface water from the southern portion of the IA flows into the SID/Woman Creek drainage. Surface water is likely to be the most important transport medium determining compliance with the RFCA and appropriate remediation performance criteria. Table 8-1 summarizes the individual actinide transport processes and potential sources within each drainage basin. The purpose of this table is to identify the processes that are expected to account for the majority of the observed actinide movement at the site. The items that are shaded in Table 8-1 identify the specific processes that are believed to be of primary importance within each of the drainage areas, essentially defining the basis for the area-specific conceptual models. The preliminary hypothesis will be reviewed with actinide migration specialists and will be incorporated into the conceptual model refinements.

8.2 TRANSPORT PROCESSES THAT MAY REQUIRE FURTHER ANALYSIS TO REFINE THE CONCEPTUAL MODEL

This report and the preliminary hypothesis for the conceptual model identified data deficiencies and areas of uncertainty in actinide transport processes. This section provides a discussion of our current understanding of the transport process and uncertainty by environmental media. Recommendations to mitigate and limit actinide migration by remedial actions is provided in Section 9.

Table 8-1

Summary of Preliminary Hypothesis of Transport Processes and Potential Sources Within the Primary Drainages[1]

TRANSPORT PROCESS	WOMAN CREEK	SOUTH WALNUT CREEK	NORTH WALNUT CREEK	INDUSTRIAL AREA
I. Air				
"Effluent" Systems	Potential source through 1989 when primary operations ceased. The recent resumption of some activities should be controlled to mitigate additional impacts.	Potential source through 1989 when primary operations ceased. The recent resumption of some activities should be controlled to mitigate additional impacts.	Potential source through 1989 when operations ceased. The recent resumption of some activities should be controlled to *mitigate additional impacts.*	Potential source through 1989 when operations ceased. The recent resumption of some activities should be controlled to mitigate additional impacts.
Soil Particulates: Disturbance	Late-1960s/early-1970s uncontrolled emissions during inventory removal at 903 Pad drum storage area. Implement control measures to mitigate potential future emissions during remediation activities on 903 Pad Area.	Late-1960s/early-1970s uncontrolled emissions during inventory removal at 903 Pad drum storage area. Implement control measures to mitigate potential future emissions during remediation activities on 903 Pad Area.	Prior Site activities may have caused low level contamination. Implement control measures to mitigate potential future emissions during closure activities on A-Series Ponds.	Prior Site activities may have caused low level contamination. Implement control measures to mitigate potential *future* emissions during IA D&D and closure activities.
<u>Windblown</u>	<u>Potential long-term source of Pu and Am due to contaminated surface soils.</u>	<u>Potential long-term source from low level Pu and Am surface soil and exposed sediment contamination.</u>	Potential long-term source from low level Pu and Am surface soil and exposed sediment contamination.	Potential ongoing source from low level Pu or Am surface soil contamination.
<u>Splash Deposit Particles</u>	<u>Potential ongoing source of Pu and Am.</u>	<u>Potential ongoing source of Pu and Am.</u>	Limited potential ongoing source of Pu and Am.	Little vegetation within the IA for this to be an appreciable ongoing source.
II. Soils				
<u>Dissolution into water and partitioning onto soils</u>	Leaching of Pu or Am does not appear to be a significant route. Subsurface U contamination in the Original Landfill/Ashpit Area may be ongoing.	Leaching of Pu or Am does not appear to be a significant route.	Leaching of U into soils beneath the Solar Ponds may have been a source of groundwater contamination. Naturally occurring U may also be a source. <u>Both sources of U will serve as a continuing source.</u>	U detected within the IA appears to be consistent with naturally occurring U, with the exception of the Solar Ponds.
Colloidal Transport	Probably *not a significant migration* process.	*Probably not a significant migration* process.	Probably not a significant migration process.	Probably not a significant migration process.
Bioturbation	Primarily within the top 6 inches and limited to 2-3 feet. Probably not a significant migration process.	Primarily within the top 6 inches and limited to 2-3 feet. Probably not a *significant migration process.*	Primarily within the top 6 inches and limited to 2-3 feet. Probably not a *significant migration process.*	Little vegetation or wildlife within the IA for this to be a significant process.
<u>Erosion by overland flow.</u>	<u>Potential long-term process for Pu and Am due to contaminated surface soils.</u>	<u>Potential long-term process due to low level Pu and Am surface soil and exposed sediment contamination.</u>	<u>Potential long-term process due to low level Pu and Am surface soil and exposed sediment contamination.</u>	<u>Potential ongoing process due to low level Pu or Am surface soil contamination.</u>
<u>Loss/deposition of windblown soils</u>	<u>Airborne transport from and to surface soils is an ongoing process.</u>	<u>Airborne transport from and to surface soils is an ongoing process.</u>	<u>Airborne transport from and to surface soils is an ongoing process.</u>	<u>Airborne transport is an ongoing process.</u>

[1] This preliminary hypothesis will be reviewed by the actinide migration specialists and be incorporated into the conceptual model refinement.

III. Groundwater				
Dissolution	Probably not significant for Pu or Am. Detections appear to be an artifact from drilling. U contamination in the Original Landfill/Ashpit Area may be ongoing.	Probably not significant for Pu or Am. Detections appear to be an artifact from drilling.	U that leached beneath the Solar Ponds and naturally occurring U may be sources of U detected in groundwater.	U detected in groundwater within the IA appears to be consistent with naturally occurring U, with the exception of the Solar Ponds.
TRANSPORT PROCESS	**WOMAN CREEK**	**SOUTH WALNUT CREEK**	**NORTH WALNUT CREEK**	**INDUSTRIAL AREA**
Colloidal Transport	Probably not a significant transport process.	Probably not a significant transport process.	Probably not a significant transport process.	Probably not a significant transport process.
IV. Surface Water				
Overland flow: Particulates	Samples collected during storm events indicate that suspended solids from surface soils and resuspension are a significant source of actinides in surface water.	Samples collected during storm events indicate that suspended solids from surface soils and resuspension are a significant source of actinides in surface water.	Samples collected during storm events indicate that suspended solids from surface soils and resuspension are a significant source of actinides in surface water.	Samples collected during storm events indicate that suspended solids from surface soils and resuspension are a significant source of actinides in surface water.
Dissolved	Not significant for Pu or Am. U contamination in the Original Landfill/Ashpit Area may be ongoing.	Not significant for Pu or Am.	Not significant for Pu or Am, and there is little U contaminated surface soil.	Not significant for Pu or Am, and there is little U contaminated surface soil.
Deposition of windblown	Airborne transport is an ongoing process, deposition of airborne particulates may contaminate surface water.	Airborne transport is an ongoing process, deposition of airborne particulates may contaminate surface water.	Airborne transport is an ongoing process, deposition of airborne particulates may contaminate surface water.	Airborne transport is an ongoing process, deposition of airborne particulates may contaminate surface water.
Groundwater Discharge: Colloids	Probably not a significant transport process.	Probably not a significant transport process.	Probably not a significant transport process.	Probably not a significant transport process. No discharge of ground-water to surface water within the IA
Dissolved	Probably not significant for Pu or Am, but a potential process for U.	Probably not significant for Pu or Am.	Probably not significant for Pu or Am, but potentially for U.	No discharge of groundwater to surface water within the IA.
Resuspension of sediments	Sampling indicates that suspended solids are a significant source of actinides.	Sampling indicates that suspended solids are a significant source of actinides.	Sampling indicates that suspended solids are a significant source of actinides.	Sampling indicates that suspended solids are a significant source of actinides.
Dissolution from sediments	Probably not significant for Pu or Am, but potentially for U.	Probably not significant for Pu or Am.	Probably not significant for Pu or Am, but potentially for U.	Not significant for uranium, Pu or Am.

Note: The underlined text indicates the processes that cumulatively account for the majority of actinide transport within each drainage

8.2.1 Surface Soil Transport

As discussed in Section 4, the two main transport pathways for actinides in surface soils are surface soil erosion to surface water and wind transport to other surface soils and to surface water. This is primarily important downslope and downwind of the 903 Pad and Lip Areas. These processes are a significant source of contamination and contaminant redistribution in both the Woman Creek and South Walnut Creek drainages. Transport of sediments in overland flow is discussed in more detail below.

The FY97 evaluation of physical speciation and the K_ds of plutonium and americium in surface soils will be used to quantify the contribution of actinide migration to groundwater via chemical transport, and the relative contribution to surface water. This is similar to the approach that was used to establish the RFCA soil action levels for VOCs that are protective of surface water via the groundwater pathway. Pond sediment K_d values will be used to quantify the chemical transport of the actinides from sediments to surface water. Both of these chemical transport processes are expected to be relatively small compared to overland transport; however, they are being addressed to assure completeness of the analysis.

8.2.2 Soil Erosion Transport

Currently two erosion models are being evaluated for selection, the RUSLE and the WEPP models. The modeling effort will begin in FY98, with results linked to the conceptual model and mass loading analysis for the Walnut and Woman Creek drainages.

The RUSLE has serious limitations in scope. The soil loss computed is a guide, not a precise estimator of soil loss. It was designed to facilitate soil conservation practices on agricultural lands. It is intended for use on a field scale rather than on a watershed scale. RUSLE has been used to estimate sediment yields, however extreme care must be taken to account for depositional areas within sub-basins. The estimated long-term average soil loss is not sediment yield from the field, but an estimate of total sediment movement by sheet and rill erosion. Sediment yield may be much less or, if ephemeral gully erosion occurs, sediment yield may be much greater than estimated.

The Water Erosion Prediction Project (WEPP) model, developed over the last 10 years by the ARS in cooperation with other federal agencies and universities, is also being evaluated. It is a process-based, distributed parameter, continuous simulation, erosion prediction model that simulates hydrologic and erosion processes on a watershed scale. It can be used to estimate soil loss, soil deposition, sediment yield and how these are distributed in space and time (ARS, 1997). This model is considered to be a great advance over all previous erosion models. Preliminary evaluation indicates that the WEPP model has the necessary capabilities to achieve the goals of the soil erosion and actinide watershed loading modeling project at RFETS.

8.2.3 Groundwater Transport

There is no evidence of a plutonium or americium "plume" of groundwater contamination (Section 5). Transport of uranium via groundwater to surface water may occur downgradient of the Solar Ponds. Surface water sampling station SW93 is in North Walnut Creek north of the Solar Ponds, at the toe of the slope, where groundwater not intercepted by the ITS surfaces in North Walnut Creek. Surface water data indicate that at SW93 uranium is associated with baseflow which is fed by groundwater.

Groundwater downgradient of the Solar Ponds contains levels of uranium that are elevated relative to the groundwater underlying most of RFETS, although not generally above background levels. The isotopic ratios of uranium isotopes in groundwater downgradient of the Solar Ponds do not indicate an anthropogenic origin.

Two groundwater wells on the south side of the IA contain isotopic ratios of uranium that may indicate anthropogenic uranium. Well 61093 is located just south of the Original Landfill, between the landfill and the SID, and Well 07391 is located several hundred feet south of the 903 Pad. While there have been surface soil detections in the general area of well 61093, subsurface soil samples did not have actinide concentrations in excess of action levels. There were no appreciable detections of uranium in surface soils either upgradient or near well 07391, nor did subsurface soil samples exceed RFCA action levels.

Key data needs (including additional interpretation of existing data) for the conceptual model to be complete are:

- Further analysis of groundwater data from the Solar Ponds Area:

  - Correlation of uranium with other analytes, including nitrate, carbonate, iron, sodium, pH, and TSS. These correlations should be performed on uranium versus each of the other major ions (as a system is better than individual comparisons); and

  - TIMS analysis of groundwater downgradient of the ponds to determine uranium isotopic ratios. At this time the conceptual model is incomplete because it is not known to what extent the observed uranium levels are due to mobilization of natural uranium or the movement of anthropogenic uranium that was introduced into the Solar Ponds.

- Temporal and TIMS isotopic analysis of existing uranium contaminated groundwater downgradient of the Original Landfill and in the well downgradient of the 903 Pad Area that showed skewed isotope ratios, to determine whether anthropogenic uranium is migrating in these areas.

- Additional analysis of the groundwater data downgradient of the Original Landfill to determine if other contaminants are migrating.

- Additional surface water sample locations in the IA to further define water quality within drainage sub-basins in an effort to isolate actinide sources.

- Analysis of surface water and sediment data to determine if actinide mass loading is related to onsite activities, or to storm events, and identify potential conditions that may result in surface water exceedances.

- Chemical and physical speciation of transported actinides and hot spots to evaluate the conceptual model and its robustness.

- Determination of actinide mobility under varying environmental conditions.

8.2.4 Surface Water and Sediment Transport

Actinide loading to surface waters has been calculated based on continuous flow monitoring. The continuous flow samplers monitor storm events as well as baseflow, so these calculations are a reasonable estimate of the amount of contaminants entering the drainages at the measurement points. The calculated loading of actinides to North Walnut Creek, South Walnut Creek, and Pond C-2, based on surface water monitoring data, is shown in Figure 6-2. The current data do not distinguish contaminant loading into Pond C-2 from the drainage via SW027 versus the loading due to flow over the low-level contaminated surface soils surrounding Pond C-2 which is not captured by SW027. The amounts actinides entering the drainages are greater than the amount leaving the ponds, based on the pond discharge data, indicating that actinides are accumulating in the pond sediments.

Although transport of plutonium- and americium-contaminated particles from surface soils to the creeks by erosional processes occurs in the Woman Creek and Walnut Creek drainages, the pond systems established and maintained by DOE inhibit sediment and actinide transport through the drainage systems. Plutonium and americium mobility in the drainages are partially controlled by management of the ponds and by controlling the timing of pond discharges.[2]

Dissolved uranium is transported in surface water and uranium-contaminated surface soils are transported in overland flow to drainages. Isotopic studies of the pond water and pond sediment indicate that depleted uranium from RFETS has accumulated in the pond system (Efurd et al., 1993). The summary information for uranium isotopes in sitewide surface water show activities significantly higher than those for background or upgradient surface water. Overall, the pond systems perform well in mitigating uranium, such that recent ambient levels of uranium in surface water leaving the site are in the same historic range as ambient levels in the 1980s used to establish the site-specific standards for uranium. No exceedances of the total uranium standard have been observed in recent years.

In order to minimize the quantity of radionuclides carried from the Site by surface water runoff, erosion control measures were implemented during FY96 and FY97 to stabilize sediment material and entrap particulate matter suspended in storm water. Drainage areas targeted for control measures were those locations identified as most likely to contribute material that could provide a transport mechanism for radionuclides in Site runoff. Watershed improvement measures are planned for future years (contingent on funding) for those areas, as indicated by water quality monitoring results, where actinide sources are suspected of contributing contaminant loading to surface water runoff.

[2] It should be noted that during occasional periods of high precipitation (every one to two years), ponds must be discharged without the normal settling time. In these situations, the degree of actinide settling is presumed to be less efficient than during routine pond operations.

A watershed surface modeling effort is planned for FY98 to help identify sources and long-term effects on water quality (Section 8.2.2). Investigation of other upstream sources of the exceedances is also necessary since the levels of surface contamination are low. The North Walnut Creek Drainage will be further examined to define the source of plutonium loading, to assist in evaluating potential sources of recent surface water exceedances and to develop a draft Conceptual Model for actinide migration. The following tasks will be performed:

- Complete inventory of plutonium, americium, and uranium in ponds, based on the FY97 data and all previous historical data;

- Review of existing data from the IA and ponds to determine source areas;

- Evaluate pond sediment grain-size data in relationship to contamination to determine what stream energy is required to erode contaminated sediments from the ponds and under what circumstances these energies are likely to occur; and

- Establish rates for each transport mechanism;

- Perform a mass loading analyses, as part of the watershed modeling effort, in order to allocate the maximum contribution of plutonium and americium to a basin that would not exceed the stream action levels under normal environmental conditions; and

- The above data would be input into the draft Conceptual Model for actinide migration and tested on the North Walnut Creek Drainage to determine site specific cleanup levels under normal environmental conditions.

Data from the FY97 and FY98 laboratory studies will be used to generate actinide mobility distribution maps under normal and abnormal environmental conditions. This information will be used to determine the probability of meeting surface water action levels for proposed remedial actions under varying environmental conditions.

8.2.5 Air Transport

The major air transport mechanism from Site closure activities is the potential airborne transport of particulates due to excavation, regrading and structure demolition. Air monitoring data will be used in air dispersion modeling to establish transport rates for remobilizing actinides during remediation activities. The existing data will be evaluated to:

- Quantify the different resuspension mechanisms at the Site using data from various resuspension studies; and using known dispersion mechanisms, develop a long-term model of actinide migration; then validate the model using monitoring data;
- Characterize the composition of actinide contaminated particles and compare the information with the observed size-activity distribution; and
- Review data to estimate settling rates of resuspended actinide-contaminated particles, for use in long-term migration scenarios.

8.3 REFERENCES

ARS, 1997, WEPP: Spilling the Secrets of Water Erosion, in Agricultural Research, April, 1997.

Efurd, D. W., Rokop, D. J., and Perrin, R.E., 1993, Characterization of the Radioactivity in Surface-Waters and Sediments Collected at the Rocky Flats Facility, Los Alamos National Laboratory, LA-UR-93-4373.

9.0 RECOMMENDATIONS

It is expected that near-term projects to evaluate and mitigate actinide migration include: (1) the planned soil remediation activities for the 903 Pad and Lip Area and surrounding actinide-contaminated soil areas; (2) watershed improvement projects currently in progress (e.g., application of road sealant, revegetation of buffer zone roads, installation of silt fences, SID improvements); and (3) containment of the Solar Pond Plume. In FY99, data from the FY97 and FY98 laboratory studies will be used to finalize the conceptual model and to generate actinide mobility distribution maps under normal and abnormal environmental conditions. This information will be used in to determine the probability of meeting surface water action levels for proposed remedial actions under varying environmental conditions. Recommendations for finalization of each of these tasks are summarized below.

9.1 903 PAD AND LIP AREA

Sampling results, erosion calculations, and surface water mass loading calculations indicate that surface water continues to be affected by contaminated soils within the 903 Pad and Lip Area, with the contaminant loading being most notable after significant storm events. Because soils in the 903 Pad and Lip Area contain plutonium and americium and these soils appear to be a source of the actinides observed in downslope surface water, an evaluation as to whether these soils cause surface water contamination exceeding RFCA action levels will be performed to determine whether soils remediation will be necessary within this area.

The goals of the proposed Actinide Migration Study work for FY98 are to quantify the rates of actinide transfer among media, and to initiate modeling and testing transport rates on proposed remediation scenarios for the 903 Pad and Lip Area, and incorporate this information into a draft Conceptual Model for actinide migration at RFETS. In order to accomplish this, the following activities will occur:

- Based on existing data, FY97 laboratory studies to determine actinide speciation and partition coefficient/investigation results on soils and sediments, FY98 soil erosion modeling, and air dispersion modeling, rates will be established for each transport mechanism (air, erosion, and leaching to groundwater) for plutonium and americium under normal environmental conditions;

- Additional laboratory studies will be conducted to determine mobility under various environmental conditions;

- A mass loading analyses will be performed in order to allocate the maximum contribution of plutonium and americium to each basin that will not exceed the stream action levels under normal environmental conditions; and

- The above information will be input into a draft Conceptual Model for actinide migration and initial testing on the watershed below the 903 Pad and Lip Area will be initiated to determine site specific cleanup levels under normal environmental conditions.

The data summarized in this report indicate that actinide loading is occurring in areas that are not affected by the 903 Pad and Lip Area or related soils. The detailed sub-basin surface water monitoring data will be examined more closely and used in conjunction with watershed modeling results to identify potential actinide source areas. The extent of remediation will be determined not only by the extent of soils contaminated above dose-based action levels, but also by determining soil contaminant levels protective of surface water quality.

9.2 SOLAR PONDS AREA

The observed nitrate/uranium groundwater contamination in the North Walnut Creek drainage may be affecting the surface water quality downgradient of the Solar Ponds. The occurrence of plutonium above the RFCA surface water standard requires additional surface water sampling in this area. The current conceptual model assumes that this contamination comes from low-level surface soil or sediment contamination; however, this is based on the spatial association of the surface contamination with the surface monitoring stations showing exceedances and must be confirmed.

An action is required to protect surface water in North Walnut Creek from contaminated groundwater originating from the Solar Ponds. There is a RFCA milestone to construct a plume containment system in FY99. In order to ensure attainment of this milestone, additional plume characterization will be conducted in FY98 to refine knowledge of the extent of the uranium and nitrate plumes originating from the Solar Ponds area. A groundwater model will be developed specifically for the Solar Pond Plume to evaluate alternatives for managing the plume. The model will incorporate FY97 data that determined site specific uranium K_ds and speciation which affect their mobility. The groundwater model will be used to help evaluate, select, and design a preferred alternative for remediation of the Solar Pond Plume.

APPENDIX A

SUMMARY OF RFETS ENVIRONMENTAL MEDIA SAMPLES BY YEAR

APPENDIX A

SUMMARY OF RFETS ENVIRONMENTAL MEDIA SAMPLES BY YEAR

Number of Soil Samples Taken at RFETS

Year	Number of Samples		
	Surface Soil	Subsurface Soils	Pits/Trenches
1988	19		
1989	0	46	
1990	6	15	
1991	38	1570	229
1992	769	1872	492
1993	829	1610	34
1994	1666	562	1
1995	92	490	
1996	58	7	
1997	1	39	

Number of Sediments Samples Taken at RFETS

Year	Number of Samples
1990	79
1991	140
1992	543
1993	160
1994	196
1995	135
1996	5
1997	25

Number of Groundwater Samples Taken at RFETS

Year	Number of Samples		
	Groundwater	Vadose Zone Extraction	Lysimeter
1989	215		
1990	815		
1991	1152		
1992	1866		
1993	1991	139	403
1994	2460		
1995	1977		
1996	557		
1997	141		

Number of Surface Water Samples Taken at RFETS

Year	Number of Samples
1989	99
1990	860
1991	1557
1992	1442
1993	913
1994	477
1995	270
1996	158
1997	216

APPENDIX B

ANALYSIS OF
ACTINIDE DISTRIBUTION AND TRANSPORT
IN SURFACE WATER

APPENDIX B: ANALYSIS OF ACTINIDE DISTRIBUTION AND TRANSPORT IN SURFACE WATER

APPENDIX B: ANALYSIS OF ACTINIDE DISTRIBUTION AND TRANSPORT IN SURFACE WATER

Research indicates a relationship may exist between radionuclide activity and total suspended solids (TSS) in surface water. Radionuclides tend to associate with particulate matter. When small mineral particles are transported in surface water runoff, radionuclides attached to the particles are transported as well. Therefore, measuring the amount of TSS in surface water runoff from a specific drainage area may provide a characteristic ratio of radionuclide activity to TSS for that basin.

The Appendix B objective is investigate the relationship of surface water radionuclide concentrations with the indicator parameters, TSS and flow rate. Appendix B consists of four major components which are 1) surface water sampling and flow measurement, 2) actinide transport analysis, 3) watershed changes and radionuclide transport, and 4) summary of findings.

B.1 SURFACE WATER SAMPLING AND FLOW MEASUREMENT

B.1.1 General Description

Protocols for collecting samples and measuring the flow of surface water runoff from the Site are designed to yield information about the migration of actinides via surface water. Results are used to facilitate management decisions to minimize the potential of offsite discharge of radionuclides in excess of established limits.

B.1.2 Surface Water Sampling Locations and Analytes

B.1.2.1 Industrial Area Runoff Sampling Locations and Analytes

Six stations discussed in this report are used, or were used in the past, to monitor surface water runoff within the IA fence boundary. These stations are listed in Table B-1 and shown in Figure 6-1.

During Water Years 1995 and 1996[1], the IA runoff locations were operated as Tier II IA Interim Measures/Interim Remedial Action (IA IM/IRA) monitoring stations and were therefore sited to monitor selected tributary IA sub-drainages. Stations GS27 and GS28 remain active as RFCA Performance Monitoring locations.

In compliance with RFCA, and in accordance with the monitoring objectives of the draft *Integrated Monitoring Plan* (IMP), Performance, New Source Detection (NSD), and Point of Evaluation (POE) monitoring is currently performed at locations within the IA and along the five main drainages between the IA and the pond systems. Either storm-event or continuous flow-paced samples are collected at each location. Samples are analyzed for radionuclides, metals, volatile organic compounds (VOCs), and TSS, depending on location. Water quality probes have recently been deployed to collect continuous 15-minute record of pH, turbidity, specific conductivity, temperature, and nitrate at NSD locations.

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[1] Water Year is defined as October 1 through September 30. For instance, Water Year 1995 is defined as October 1, 1994 through September 30, 1995.

Table B-1. Summary Information for Surface Water Sampling Locations

Station	Drainage	Location Description	Operation Period	Projects	Sample Types	Average Annual Yield (acre-feet)
Industrial Area Runoff Sample Locations						
GS27	SWC	ditch NW of Building 889	1995 - present	IM/IRA Tier II; RFCA Perf.	Flow-paced Storm-Event	0.28
GS28	SWC	Ditch NE of Building 889	1995 - present	IM/IRA Tier II; RFCA Perf.	Flow-paced Storm-Event	1.13
GS21	SID	small culvert SE of Bldg. 664	1995 -1996	IM/IRA Tier II	Flow-paced Storm-Event	2.13
GS22	SID	outfall at SID of 400 Area culvert	1995 -1996	IM/IRA Tier II	Flow-paced Storm-Event	37.50
GS24	SID	small culvert S of Bldg. 881	1995 -1996	IM/IRA Tier II	Flow-paced Storm-Event	0.84
GS25	SID	ditch draining SE of Bldg. 881	1995 -1996	IM/IRA Tier II	Flow-paced Storm-Event	5.41
Detention Pond Influent Sample Locations						
SW093	NWC	N. Walnut Cr. Upstream from the A-1 bypass	1991 - present	Event-Related; IM/IRA Tier I; RFCA NSD, ALF	Flow-paced Storm-Event, Continuous	118.7
SW091	NWC	Gully NE of Solar Ponds tributary to N. Walnut Creek	1995 - present	IM/IRA Tier I; RFCA NSD	Flow-paced Storm-Event	1.38
SW022	SWC	Central Ave. Ditch at Inner East Fence	1995 - present	IM/IRA Tier I; RFCA NSD	Flow-paced Storm-Event	29.40
GS10	SWC	S. Walnut Creek upstream from the B-1 bypass	1991 - present	Event-Related; IM/IRA Tier I; RFCA NSD, ALF	Flow-paced Storm-Event, Continuous	85.40
SW027	SID	South Interceptor Ditch at Pond C-2	1991 - present	Event-Related; IM/IRA Tier I; RFCA NSD, ALF	Flow-paced Storm-Event, Continuous	32.80
Detention Pond Effluent Sample Locations						
Pond A-4	NWC	Terminal pond in N. Walnut Ck.	N/A (see Note 2)	NPDES, RFCA	Composited grabs during discharge	387 (See Notes)
Pond B-5	SWC	Terminal pond in S. Walnut Ck.	N/A (see Note 2)	NPDES, RFCA	Composited grabs during discharge	258
Pond C-2	SID	Terminal pond in SID/Woman Ck.	N/A (see Note 2)	NPDES, RFCA	Composited grabs during discharge	33

Notes:

1) All values are based on record from Water Year 1995 through March 1997 (if applicable) and some recent data are preliminary and subject to revision.
2) Sampling periods for this pond discharge data are: Pond A-4, 1/91 to 6/96; Pond B-5, 3/94 to 6/95; and Pond C-2, 3/92 to 6/95.
3) NWC = North Walnut Creek; SWC = South Walnut Creek; SID = South Interceptor Ditch
4) Monitoring locations shown on Figure 6.1 in main text.

B.1.2.2 Detention Pond Influent Sampling Locations and Analytes

Five stations are used to monitor surface water influent to the detention ponds (see Table B-1). Originally, automated sampling was performed at these locations as part of the Event-Related Surface Water Monitoring program conducted from the early 1990's through 1994. Under this program, the normal sampling protocol was flow-paced storm-event sampling for radionuclides, metals, and water quality parameters. Data reports, some with data analysis, were produced for Water Years 1991-92, 1993, and 1994 (EG&G, 1993, 1994, and 1995).

During Water Years 1995 and 1996, these locations were operated as Tier I IA IM/IRA monitoring stations located on the five main drainage pathways to the ponds.

B.1.2.3 Detention Pond Effluent Sampling Locations and Analytes

Detention Pond effluent data analyzed for this study were collected at the outfalls of the three detention ponds furthest downstream in their respective drainages: Ponds A-4, B-5, and C-2, commonly referred to as the "Terminal" Ponds. Surface water runoff from the IA ultimately is collected in these Terminal Ponds, where it is sampled prior to batch discharge from the Site. The majority of water discharged offsite from the North and South Walnut Creek drainages is routed through Pond A-4. Direct offsite discharges from Pond B-5 occur occasionally (typically once every one to two years), during periods of high precipitation, when the pond system is filled to the limit of safe capacity and an emergency discharge is required. Scheduled offsite discharges from Pond C-2 also occur, on average, once a year.

B.1.3 Sampling Methodologies

B.1.3.1 Industrial Area Runoff and Detention Pond Influent Sampling

Two distinct automated sample collection methods, continuous and storm-event sampling, are employed per the draft IMP to monitor actinide activity of surface water runoff from the IA into the detention ponds (Kaiser-Hill, 1997). Though analytical results from both sampling protocols may be used to identify changing trends in surface water actinide activity, the two protocols generate results which generally serve different purposes and require unique interpretations.
Both continuous and storm-event samples are composites of multiple flow-paced discrete grabs collected by automated sampling equipment. However, the time span over which the discrete grab samples are collected differs between the two methods. The objective of storm-event sampling is to collect a flow-paced composite for the time of increasing stage (rising limb) during a storm-event hydrograph. In contrast, continuous flow-paced composites are comprised of grab samples taken over the entire hydrograph for an estimated discharge volume. When a continuous flow-paced composite is removed from the field, a new composite is started immediately.

Analytical results of continuous flow-paced samples are representative of what may be considered the average activity of a given analyte for the surface water discharge over the sampling period. This information can be used to estimate the total mass of constituent migration in the surface water during the sampling period.

In contrast to continuous sampling, storm-event sampling is performed to assess storm-event mobilization of constituents. The goal of sampling during the rising limb of the hydrograph is to collect composite samples containing only aliquots with the likelihood of having the greatest concentration of mobilized, dissolved, or particle-bound constituents. Because this sample type contains exclusively storm-event mobilized actinides, analytical results may provide insight as to the mechanisms of mobilization and transport. Additionally, these types of samples may be used to evaluate relationships between flow rates, radionuclides, and water quality parameters.

B.1.3.2 Detention Pond Effluent Sampling

Data presented for detention pond effluent sampling are from grab samples collected once per day, then composited, for discharges from Terminal Ponds A-4, B-5, and C-2 from 1991 through 1996 (dates vary for each pond and are noted in Table B-1).

B.1.4 Flow Monitoring

Past sampling and flow monitoring indicate that, as the magnitude of flow increases, the level of plutonium and americium activity in surface water tends to increase (DOE, 1996). The relationship between uranium and flow is variable and dependent on location than plutonium and americium. This phenomena is caused by increased suspended solids in surface water at higher flow rates. Flow monitoring therefore represents an important component of the overall surface water actinide transport analysis.

B.1.4.1 Flow Monitoring for Industrial Area Runoff and Detention Pond Influent

Flow rates are automatically measured at the monitoring stations for IA runoff and detention pond influent. For each sample collected, a corresponding flow rate is recorded at the time of sample collection. The existence of quantifiable relationships between flow and surface water actinide activity, unique for each monitoring location, can hence be examined.

Surface water flow rates at the six gaging stations monitoring runoff from the IA (see Table B-1) vary significantly in magnitude and occurrence. Baseflow is generally not observed at these stations; recorded flow at these locations is attributed exclusively to stormwater runoff. The flow rates and annual yields for these locations are directly dependent on sub-drainage characteristics such as area, gradient, and percent imperviousness. Annual yields for these stations are presented in Table B-1.

In contrast to the IA runoff stations, two of the detention pond influent stations, SW093 (North Walnut Creek) and GS10 (South Walnut Creek), receive nearly continuous baseflow throughout the year. The other three detention pond influent stations discussed in this report (SW091, SW022, and SW027) receive intermittent flow.
For comparison between all IA runoff and detention pond influent stations, average annual yields (acre feet per year) are presented in Table B-1.

B.1.4.2 Flow Monitoring for Detention Pond Effluent

Correlations between flow and radionuclide activity are not presented for effluent from the Terminal Ponds. Water discharged from the ponds comes from the mid- to upper portion of the water column (utilizing a standpipe for Pond A-4 outlet works discharges and floating inlets for pumping from Ponds B-5 and C-2). Consequently, flow rates of pond effluent water do not influence suspended solids concentration or radionuclide activity in water being discharged from the ponds.

B.2 ACTINIDE TRANSPORT ANALYSIS

Analysis of data involving actinide transport in surface water is divided into the following categories:

- Variation of radionuclide activity by location and sampling methodology;
- Relationships between radionuclides, TSS, and flow; and
- Impact of watershed changes on radionuclide transport (at those sites where employed).

Based on relevant surface water actinide sampling results, correlations of relationships between radionuclide activities, TSS, and flow are discussed below.

B.2.1 Variation of radionuclide activity by location and sampling methodology

A summary of radionuclide activities measured at surface water sampling stations is provided in Table B-2. This provides an insight into the relative magnitude of activities, categorized by drainage, measured at IA runoff stations versus detention pond influent and effluent locations. Dates of operation for these gaging stations were identified in Table B-1.

Table B-2 Radionuclide Activities by Surface Water Sample Location

Station	Drainage	Sample Type	# of samples (n)	Avg. Pu-239,-240 (pCi/L)	Avg. Am-241 (pCi/L)	Avg. Total Uranium (pCi/L)
Industrial Area Runoff Sample Locations						
GS27	SWC	Storm Only	13	24.98	9.06	1.47 (n = 12)
GS28	SWC	Storm Only	11	0.156	0.061	0.676
GS21	SID	Storm Only	10	0.033	0.023	0.801
GS22	SID	Storm Only	8	0.0128	0.0178	0.710
GS24	SID	Storm Only	11	0.0931	0.031	1.4811
GS25	SID	Storm Only	9	0.018	0.012	1.518
Detention Pond Influent Sample Locations						
SW093	NWC	Storm & Continuous	36	0.409	0.198	3.266
SW093	NWC	Storm Only	17	0.816	0.396	2.149
SW093	NWC	Continuous	19	0.044	0.020	4.265
SW091	NWC	Storm Only	8	0.498	0.515	4.771
GS10	SWC	Storm & Continuous	67	0.195	0.166 (n = 66)	2.336
GS10	SWC	Storm Only	49	0.228	0.200 (n = 48)	2.069
GS10	SWC	Continuous	17	0.112	0.075	2.975

Station	Drainage	Sample Type	# of samples (n)	Avg. Pu-239,-240 (pCi/L)	Avg. Am-241 (pCi/L)	Avg. Total Uranium (pCi/L)
SW022	SWC	Storm Only	16	0.187	0.075	0.958; (n = 15)
SW027	SID	Storm & Continuous	18	0.305	0.058 (n = 17)	2.859
SW027	SID	Storm Only	14	0.385	0.074 (n = 13)	3.247
SW027	SID	Continuous	4	0.022	0.005	1.502
Detention Pond Effluent Sample Locations						
Pond A-4	NWC	Compos. grabs	139	0.007	0.008	1.789
Pond B-5	SWC	Compos. grabs	9	0.022	0.011	2.272
Pond C-2	SID	Compos. grabs	9	0.100	0.017	2.797

Notes: 1) Averages are calculated as arithmetic averages of individual carboy results.
2) As noted, in some cases, the analyte's average activity is based on a different number of "n" samples.

B.2.1.1 Plutonium and Americium Observations

From data presented in Table B-2, the following *general* observations may be made from the Pu-239/240 and Am-241 activities measured at surface water monitoring locations.

- At stations where both storm event and continuous flow samples have been collected (stations SW093, GS10, SW027 - located at the influent to Ponds A-4, B-5, and C-2, respectively), storm event samples contain significantly higher plutonium and americium activities than continuous flow samples collected at the same location. This variation is consistent when plutonium and americium are preferentially associated with particulate matter in the water column.

- Radionuclide activities in detention pond stormwater influent may be one to two orders of magnitude higher than the activities associated with the detention pond effluent. This indicates that the settling of particulate matter occurring in the ponds removes radionuclides from the water column[2].

[2] Pond C-2 is the exception; effluent activities from this pond are skewed higher by samples collected in Spring 1995.

From the data in Table B-2, the following *location-specific* observations may be made from the Pu-239/240 and Am-241 activities measured at surface water monitoring locations.

- Plutonium and americium activities measured at IA runoff station GS27 during storm events are the highest measured at any automated monitoring location; a maximum value of 90 pCi/L was measured on June 28, 1997. Initially, a significant source upgradient of GS27 was suspected, however, surveys and soil sampling did not indicate the presence of a 'hot spot' or significant source.

- By simply comparing the arithmetic average plutonium activities for storm event samples at IA runoff station GS27 and pond influent station SW022, coupled with each location's corresponding annual surface-water yield, suggests the GS27 sub-drainage may be contributing a significant portion of the plutonium load to SW022 (and hence to the South Walnut Creek drainage).

- SW022 has plutonium and americium activities of similar magnitude to GS10, and represents approximately 34% of the surface water runoff entering South Walnut Creek from the IA. Although SW022 measures runoff from the portion of the Site associated with uranium, it still represents a significant portion of the total actinide load, inclusive of plutonium and americium, to South Walnut Creek.

- Although station SW091 (Pond A-4 influent) has activities of similar magnitude to the other Pond A-4 influent location (SW093), SW091 represents only 1% of the surface water entering North Walnut Creek from the IA; and therefore comprises only a small portion of the total actinide load to North Walnut Creek.

- Comparing the arithmetic average plutonium activities for stormwater samples at IA runoff stations GS21, GS22, GS24, and GS25 (sub-basin monitoring upstream from station SW027) with station SW027 (Pond C-2 influent), coupled with each location's corresponding annual surface-water yield, suggests that none of these IA locations is contributing a significant portion of the plutonium load to SW027. This in turn, suggests that the source for the activity measured at SW027 probably originates downstream from these gages (GS21, GS22, GS24, and GS25) in areas affected by contamination from the 903 Pad.

- Although Pond C-2 generally shows higher plutonium activities than Ponds B-5 and A-4, station SW027 (influent to Pond C-2) has lower average plutonium activities for continuous samples than do the stations that monitor the influent to Ponds A-4 and B-5 (SW093 and GS10, respectively).

B.2.1.2 Uranium Observations

From the data presented in Table B-2, the following *general* observations may be made from the uranium activities measured at surface water monitoring locations.

Surface water data from monitoring locations with baseflow near the Solar Ponds suggest as surface water flow rate increases due to storm events, uranium activity decreases with dilution of baseflow. This trend is evident in the results from gaging station SW093 downgradient from the Solar Ponds. This phenomenon may be due to groundwater, which supplies the baseflow and is the primary source for uranium observed in the surface water. This conclusion is further supported by data from monitoring locations with ephemeral flow which exhibit no significant relationship between total uranium and flow rate. At stations with baseflow, the primary mechanism for uranium contamination of surface water may not be mobilization of particle-bound nuclides by storm events, but transport via groundwater supply of baseflow.

From the data presented in Table B-2, the following *location-specific* observations may be made from the uranium activities measured at surface water monitoring locations.

- Total uranium increased significantly at SW093 (Pond A-4 influent) for continuous samples compared to storm events. This result suggests that uranium may be preferentially associated with baseflow at this location, especially groundwater seeps. This is consistent when storm events occur, overland runoff causes dilution of the uranium contained in the baseflow and, hence, the storm event samples contain lower total uranium activity than the continuous flow samples. The proximity of SW093 to the Solar Ponds could also be influencing the total uranium data due to a hydraulic connection (e.g., seep) between the Solar Ponds, a uranium source, and North Walnut Creek upstream of SW093.

- Measurably less uranium is observed at SW027 (Pond C-2 influent) for continuous samples compared to storm events. This suggests that for this location uranium may be preferentially associated with storm runoff. It may also indicate that the source of baseflow may be low in uranium, or that baseflow from natural sources is minimal at this location. In fact, SW027 does not receive baseflow much of the year, and when it does, this baseflow (or a significant portion) may originate as a domestic leak flowing into the 400 Area stormwater collection system.

Uranium in surface water drainages is associated with baseflow in areas that drain the Solar Ponds (SW093, GS10), but appears to be associated with storm runoff in the areas south of Building 881 and the Original Landfill (monitored by SW027), where there is known surface uranium contamination. Total uranium activity is similar for the effluent from all three terminal detention ponds (Ponds A-4, B-5, and C-2). In North Walnut Creek, Pond A-4 (1.8 pCi/L) contains roughly one-fourth the total uranium activity of the continuous flow for SW093, (4.3 pCi/L) which is located below the Solar Ponds. In South Walnut Creek, Pond B-5 (2.3 pCi/L) total uranium activity is slightly lower than the continuous flow sampled at GS10 (3 pCi/L). In the SID, Pond C-2 (2.8 pCi/L total uranium) contains slightly lower total uranium than is recorded for SW027 (3.2 pCi/L).

B.2.2 Relationships between radionuclides, suspended solids, and flow

In order to understand the relationships between the actinides of concern, suspended solids and flow, plots were developed relating these variables to one another for each of the surface water sampling stations. These plots included:

- Plutonium activity versus flow;
- Americium activity versus flow;
- Total uranium activity versus flow;
- Plutonium activity versus TSS; and
- Americium activity versus TSS.

The results of these evaluations are summarized in Table B-3. Where trends from the regressions, whether positive or negative, were observed, they are noted with (+) or (-) signs, respectively. When the regression R^2 value is greater than 0.90, the trend is noted with (+) or (-) signs underlined and the R^2 value is listed in the Correlation Notes column of the table. Potential implications of these relationships are also noted in the last column. A detailed discussion of these relationships is provided and summarized according to each sampling location.

A discussion of these relationships, as observed for each sampling location, is provided in the following sections. Although plutonium, americium, and uranium, were plotted versus flow, only plutonium and americium were plotted against TSS because a uranium/TSS relationship has historically not been observed. In those cases where, for a specific monitoring location, a trend between an actinide versus flow or TSS was not observed, then a discussion of the trend is frequently not discussed.

B.2.2.1 Station GS27

Gaging Station GS27 is located in a ditch northwest of Building 889. GS27 was installed as an IA IM/IRA Tier I location, and is currently operated under RFCA as a Performance Monitoring location. This small IA sub-basin has no baseflow.

Table B-3 Summary of regressions between radionuclides, flow, and suspended solids.

Station	Drainage	Sample Type	# of samples (n)	Pu vs. flow trend	Am vs. Flow trend	Tot U vs. flow trend	Pu/Am vs. TSS trend	Correlation Notes / (Implications)
Industrial Area Runoff Sample Locations								
GS27	SWC	Storm Only	13	(+)	(+)	none	(+)	Am vs. TSS: $R^2 = 0.89$ (Minimizing erosion could minimize rad transport)
GS28	SWC	Storm Only	11	none	none	none	<u>(+)</u>	Pu vs. TSS: $R^2 = 0.92$ (Minimizing erosion could minimize rad transport)
GS21	SID	Storm Only	10	(+)	(+)	none	none	low activity in samples
GS22	SID	Storm Only	8	(+)	(+)	none	none	low activity in samples
GS24	SID	Storm Only	11	(+)	(+)	none	none	low activity in samples
GS25	SID	Storm Only	9	(+)	(+)	none	none	low activity in samples
Detention Pond Influent Sample Location								
SW093	NWC	Storm & Continuous	36	none	none	(-)	(+)	(Tot. U contained in baseflow, diluted by stormwater)
SW091	NWC	Storm Only	8	<u>(+)</u>	<u>(+)</u>	none	<u>(+)</u>	Pu vs. flow: $R^2 = 0.96$ Pu vs. TSS: $R^2 = 0.92$ (Minimizing erosion could minimize rad transport)
GS10	SWC	Storm Only	48	none	none	none	(+)	Pu vs. TSS: $R^2 = 0.89$
SW022	SWC	Storm Only	16	none	none	none	(+)	(Large basin variability possible cause for weak correlations).
SW027	SID	Continuous	4	(+)	(+)	(-)	none	(Low TSS at SW027 makes TSS trending difficult.)

Notes: (1) Activities are measured as pCi/L; Flow is measured as cfs; TSS is measured as mg/L.
(2) Where trends from the regressions, whether positive or negative, were observed, they are noted with (+) or (-) signs, respectively. (3) When the regression R^2 value is greater than 0.90, the trend is noted with (+) or (-) symbols underlined and the R^2 value is listed in the Correlation Notes column of the table.

General Water Quality Summary for GS27

Stormwater activities measured at GS27 are the highest measured at any monitoring location to date; a maximum value of 90 pCi/L has been measured. Initially it was assumed that a significant source had been discovered. However, soil sampling did not indicate a "hot spot" or significant source. Therefore it was theorized that the source was distributed over a large portion of the drainage basin, because several samples were collected that exceeded 1×10^1 pCi/L plutonium activity. In response, watershed improvements, including the removal of sediments and the application of a soil sealant, were implemented (as described in B.3.2). Surface water monitoring is ongoing to determine the effectiveness of these measures (as described in B.3.3).

Comparing the arithmetic average plutonium activities for storm samples at GS27 and SW022, coupled with each location's corresponding annual surface-water yield, indicates that the GS27 sub-drainage is contributing a significant portion of the plutonium and americium load to SW022.

Relationship Between Radionuclides and Suspended Solids for GS27

Results of plutonium, americium, and TSS analyses of storm water from GS27 exhibit good correlation between actinide activity and suspended solids. Data from GS27 are presented in Figure B-2. The strong correlation may be attributed to the small drainage area (less than 1 acre each) monitored by this station; however, it should be noted that only limited data sets are available for this location, and the relationship is influenced by samples with high activity.

Relationship Between Radionuclides and Flow Rates for GS27

Total uranium exhibits a weak correlation between activity and flow. The lack of relationship between uranium and flow can be attributed to a lack of uranium source in the

GS27 sub-basin; measured uranium activities are low whether there is high flow or not. No baseflow exists that contains elevated uranium activity. Plutonium and americium also exhibit weak correlations, but positive trends, between activity and flow (Figure B-3). Plutonium and americium do exist in this basin, and the positive trend between these actinides and flow supports the theory that plutonium and americium are associated with particulate matter that is increasingly mobilized as flow increases.

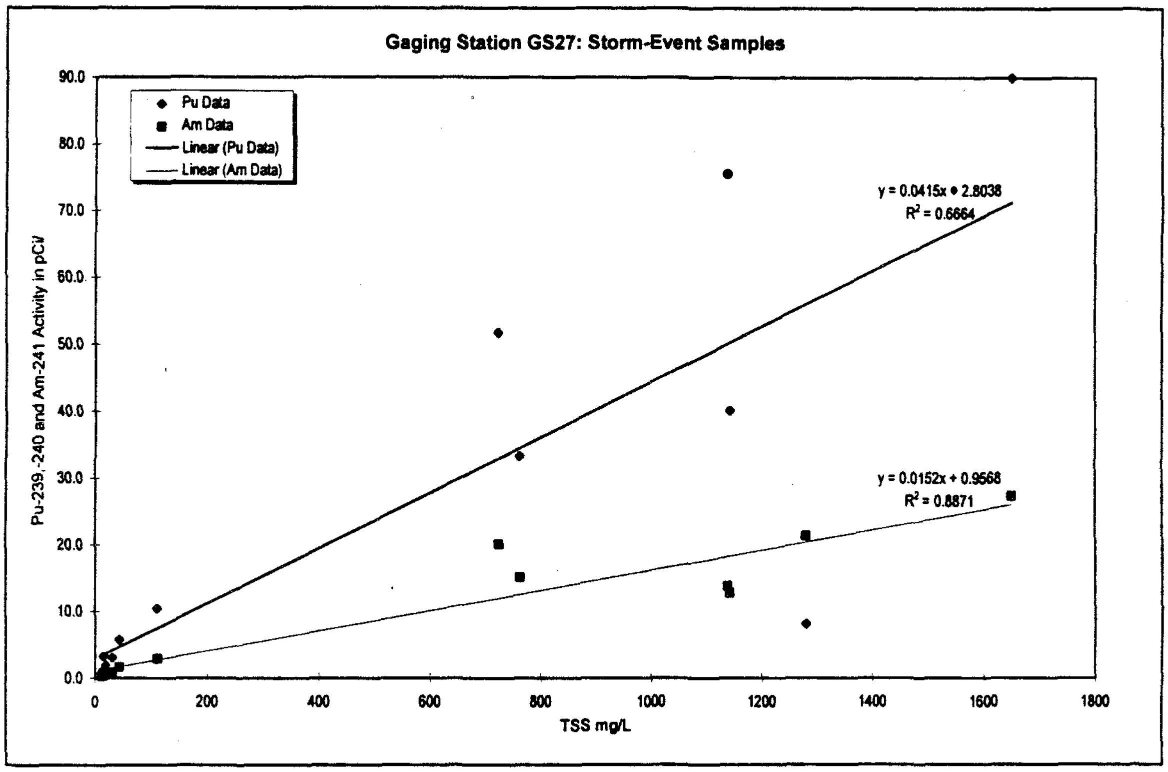


Figure B-2. Station GS27: Variation of Pu-239,240 and Am-241 Activities with TSS

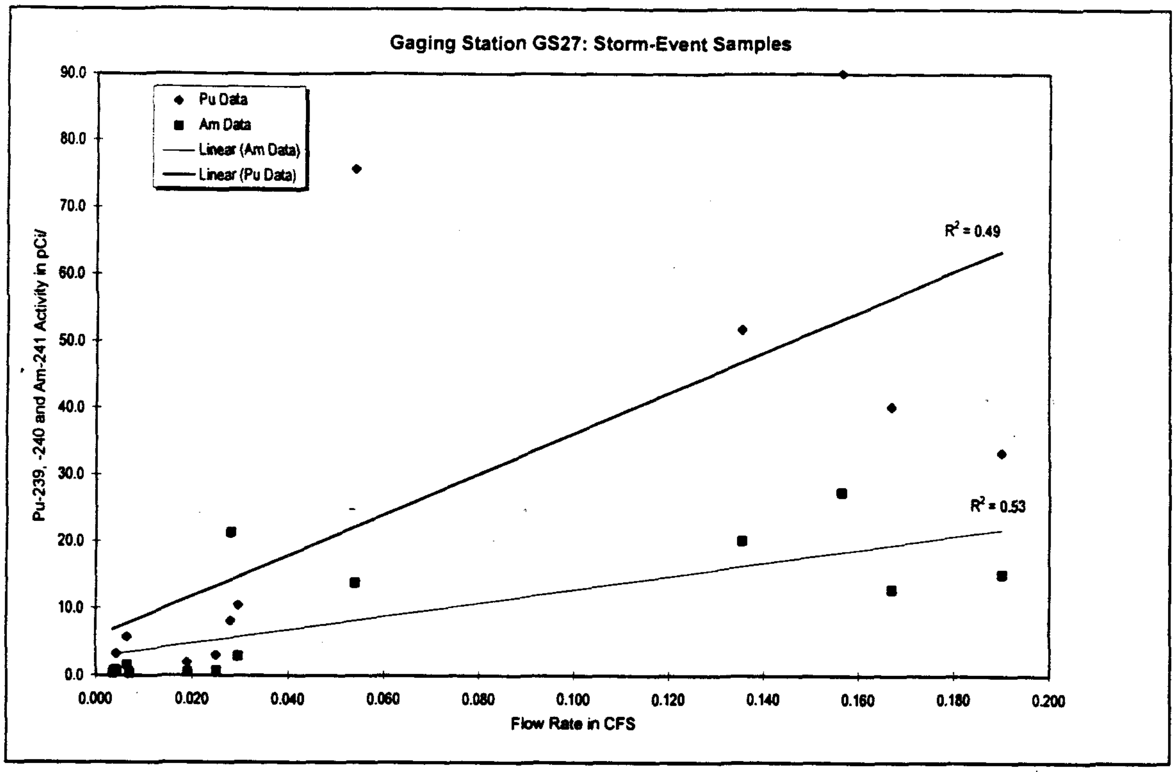


Figure B-3. Station GS27: Variation of Pu-239,240 and Am-241 Activities with Flow

B.2.2.2 Station GS28

Gaging Station GS28 is located in a ditch northeast of Building 889. GS28 was installed under the IM/IRA as a Tier II location, and is currently operated under RFCA as a Performance Monitoring Location.

Relationship Between Radionuclides and Suspended Solids for GS28

Results of plutonium, americium, and TSS analyses of storm water from GS27 and GS28 exhibit good correlations and similar trends between actinide activity and suspended solids. Data from GS28 is presented in Figure B-4. The strong correlations may be attributed to the small drainage areas (less than 1 acre) monitored by this station; however, it should be noted that only limited data sets are available for this location, and the relationships are strongly influenced by samples of higher activity.

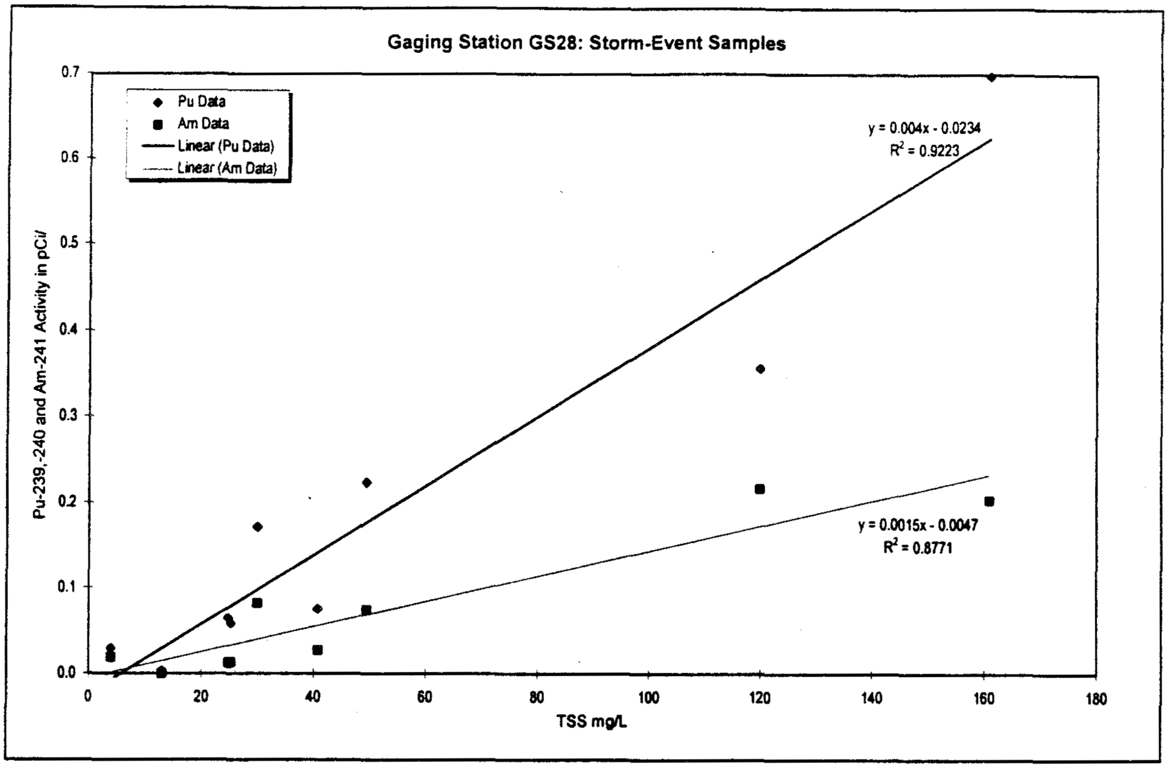


Figure B-4. Station GS28: Variation of Pu-239,240 and Am-241 Activities with TSS

B.2.2.3 Stations GS21, GS22, GS24, and GS25

Gaging Stations GS21, GS22, GS24, and GS25 were all located within small drainages entering the SID. GS21 was in a small culvert southeast of Building 664; GS22 was in the outfall from the 400 Area at the SID; GS24 was in a small culvert south of Building 881; and GS25 was in the ditch southeast of Building 881. Storm-event samples were collected at these locations when they were operated to collect surface water baseline information for the IA IM/IRA from 1995 to 1996.

<u>General Water Quality Summary for GS21, GS22, GS24, and GS25</u>

Comparison of the arithmetic average plutonium activities for storm samples at the above locations and SW027, coupled with each location's corresponding annual surface-water yield, indicates that none of these locations are contributing a significant portion of the plutonium load to SW027. This supports the conclusion that the source for the activity measured at SW027 probably originates downstream from these gaging stations (GS21, GS22, GS24, and GS25) in areas affected by contamination from the 903 Pad.

Relationship Between Radionuclides and Suspended Solids for GS21, GS22, GS24, and GS25

Data from storm-event samples from GS21, GS22, GS24, and GS25 exhibit no significant correlation between radionuclides and TSS. Only results from GS24 show even an apparent positive trend for plutonium versus TSS. These gaging stations all monitor fairly small basins; however, the lack of good correlations may be attributed to the overall low radionuclide activity in all the samples. Even the samples with the highest activities yielded actinide levels of similar magnitude to the reported analytical error. As a result, comparison of variation among the samples is not meaningful.

Relationship Between Radionuclides and Flow Rates for GS21, GS22, GS24, and GS25

These IA sub-basins are similar to GS27 with respect to size, lack of baseflow, and similar radionuclide activity to flow relationships. Total uranium exhibits a weak correlation between activity and flow. The lack of relationship can be attributed to a lack of uranium source in these sub-basins; measured uranium activities are low whether there is high flow or not. Baseflow does not exist that contains elevated uranium activity. Plutonium and americium also exhibit weak correlations, but with positive trends, between activity and flow (Figure B-5). The positive trend between plutonium and americium with flow supports the theory that plutonium and americium associates with particulate matter that is increasingly mobilized as flow increases. Although discussions of results are provided for stations GS21, GS22, GS24, and GS25, only the activity versus flow plot for GS24 is provided because it is representative of the trend observed at each of these stations.

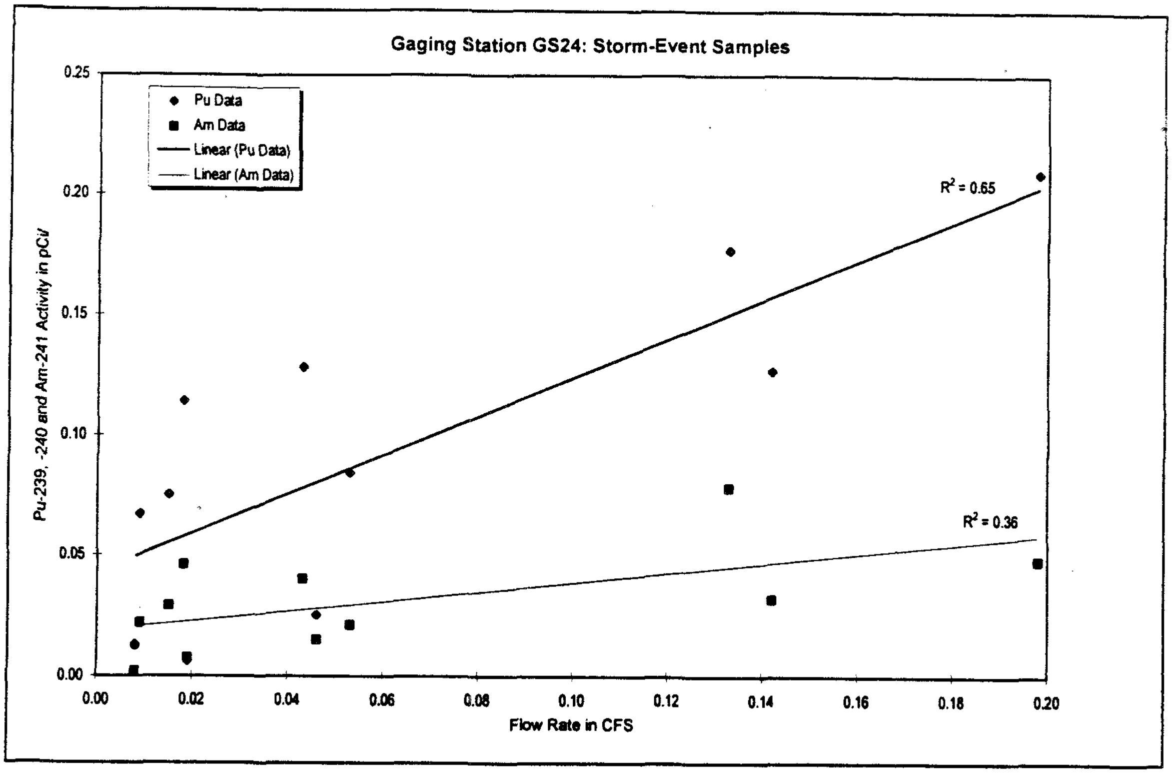


Figure B-5. Station GS24: Variation of Pu-239,240 and Am-241 Activities with Flow

B.2.2.4 Station GS32

Only one Performance Monitoring location is currently installed in the IA which is tributary to North Walnut Creek. Monitoring location GS32 was installed toward the end of FY96 to support D&D activities for Building 779, with three samples collected to date and only one result returned to date. Due to difficulties with the discharge point, accurate flow measurement is impractical and, therefore, samples are time-paced. Although TSS and radionuclide data are collected, lack of flow measurement will make transport analysis for this location difficult. Historically, no automated sampling has occurred in these sub-drainages.

B.2.2.5 Station SW093

General Water Quality Summary for SW093

Gaging station SW093 is located along North Walnut Creek, upstream from the A-1 bypass, and monitors surface water from the north part of the IA. Previously SW093 served as a gaging station for the Event-Related Surface-Water Monitoring Program and as a Tier I location for IM/IRA. Currently, SW093 is a POE and NSD location under RFCA, collecting continuous flow-paced samples.

The summary values in Table B-2 indicate that there is a significant increase in plutonium and americium in storm-event samples at SW093 compared to continuous samples. This variation is expected if it is assumed that plutonium and americium are preferentially associated with particulate matter in the water column. Storm-event samples consist of grabs taken during high flow rates on rising limbs and therefore have higher TSS concentrations.

Total uranium activity at SW093 is significantly higher for continuous samples compared to storm-event samples. This suggests that uranium, at this location, may be preferentially associated with baseflow. If uranium was associated with groundwater seeps, it would be at higher activities during baseflow than during storm events where large amounts of overland runoff is available for dilution. The proximity of SW093 to the Solar Ponds could also be influencing the total uranium data due to a hydraulic connection (e.g., seep) between the Solar Ponds, a uranium source, and North Walnut Creek upstream of SW093.

Relationship Between Radionuclides and Suspended Solids for SW093

Plutonium and americium activities from storm-event samples collected from gaging station SW093 show a general positive trend for activity versus TSS, although statistical correlations for these relationships are weak. It is hypothesized that the absence of a statistically significant relationship may be attributed to the relatively large size of the drainage basin. A larger basin is likely to exhibit greater variability in contaminant distribution as well as rainfall intensity distribution among events. These factors combine to yield variable exposure of runoff waters to contaminated soils. For instance, a large storm event may produce rainfall on those areas of the drainage basin with minimal radionuclide content in the soil, while another, similarly large storm event may produce rainfall primarily on areas in the basin with significant contamination. Both events of similar intensity might suspend similar concentrations of solids; however, the actinide levels in the samples would be quite different. Consequently, storm-event samples from large basins may not be as readily comparable as those from smaller drainages.

Relationship Between Radionuclides and Flow Rates for SW093

Monitoring results from station SW093, which include storm-event and continuous flow-paced samples, show a negative relationship between flow and total uranium activity (Figure B-6). Station SW093 receives near-continuous baseflow. These results indicate that runoff from storm events dilutes the total uranium activity in the baseflow and causes lowered activities at higher flow rates. A possible explanation for this phenomenon is that contaminated groundwater supplying the baseflow constitutes the primary source for total uranium observed in the surface water.

No relationship was observed for plutonium and americium activities as a function of flow at station SW093. This is expected as SW093 monitors a large, complex basin and no significant relationship was observed between plutonium/americium activities with TSS.

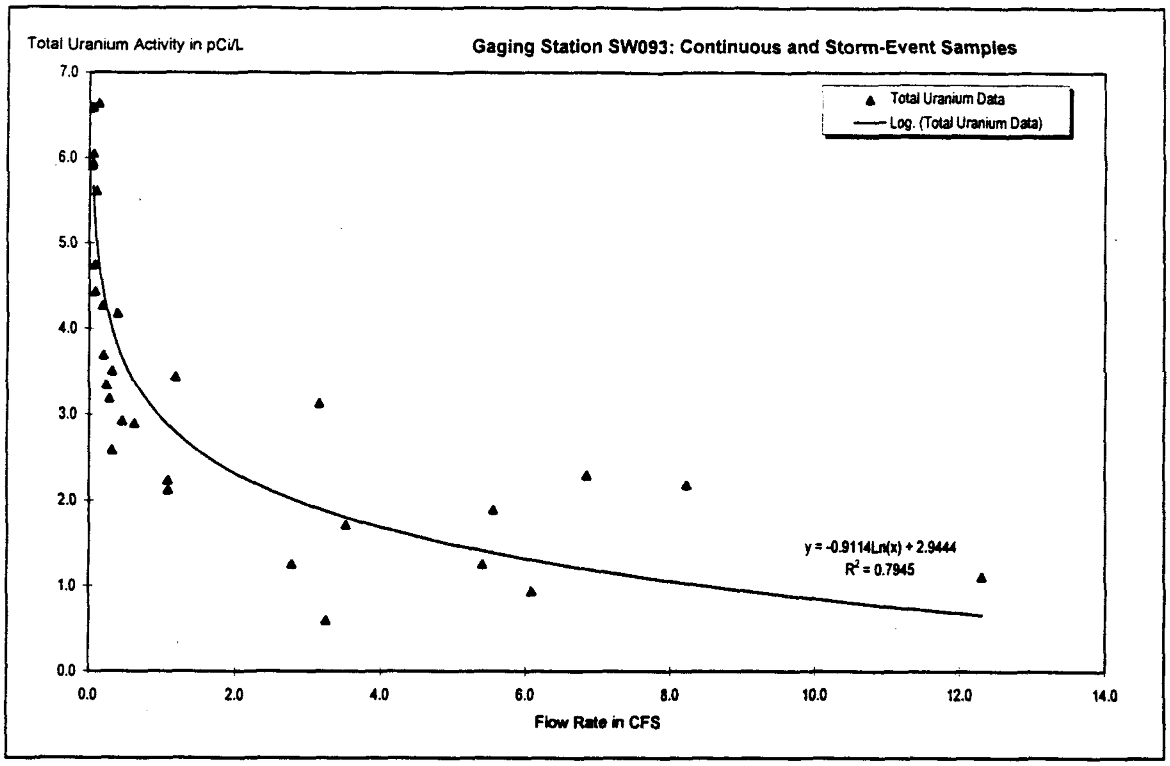


Figure B-6. Station SW093: Variation of Total Uranium Activity with Flow

B.2.2.6 Station SW091

Gaging station SW091 is located in a gully northeast of the Solar Ponds, and is tributary to North Walnut Creek. SW091 previously served as an IA IM/IRA location and now serves as a NSD Location under RFCA, collecting storm-event samples. The drainage basin is comprised largely of the dirt yard east of the Solar Ponds.

General Water Quality Summary for SW091

Although SW091 shows activities of similar magnitude to SW093, it represents approximately 1% of the surface water entering North Walnut from the IA, and therefore only a small portion of the total sediment load to North Walnut Creek.

Relationship Between Radionuclides and Suspended Solids for SW091

Significant, positive correlations for plutonium and americium activities with TSS exist for storm-event samples collected from gaging station SW091 (Figure B-7). Like SW093, gaging station SW091 monitors surface-water influent to the A-series ponds in North Walnut Creek; SW091, however, drains a smaller basin. The smaller size of the basin may account for the improved correlation due to reduced spatial variability of precipitation intensity. These correlations are based on relatively small data sets (n=8); consequently, the relationship is strongly influenced by the points of high activity.

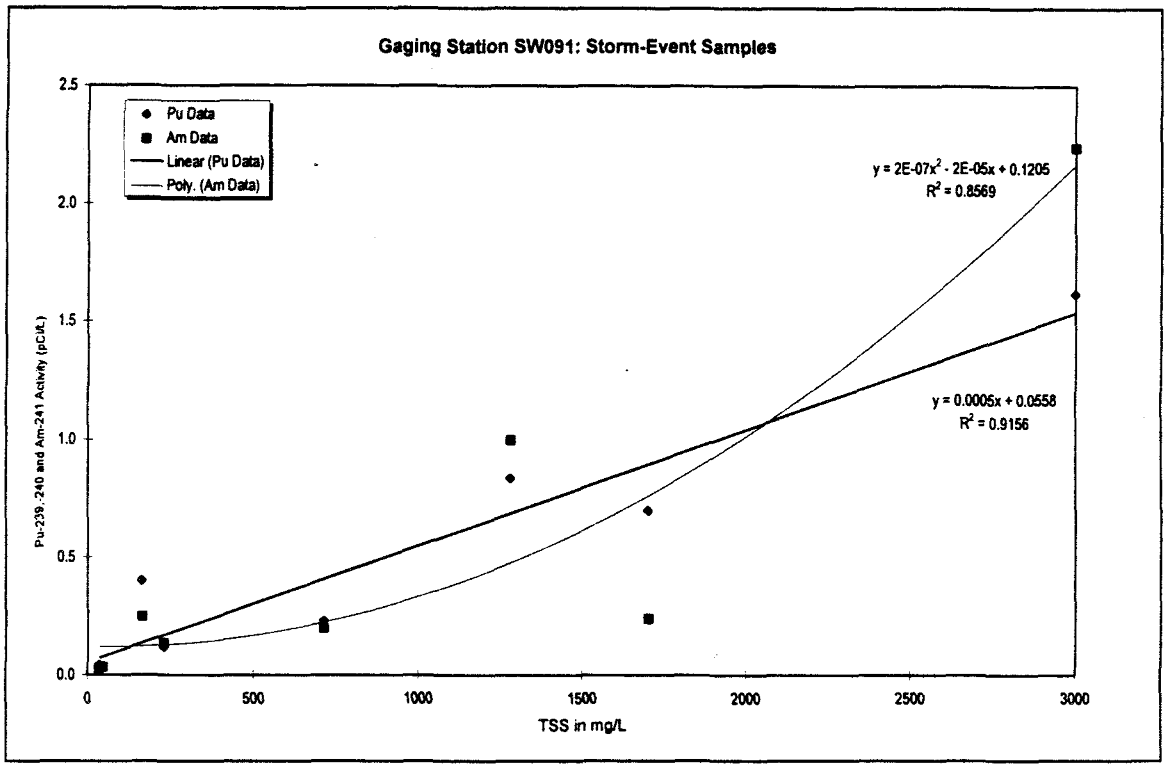


Figure B-7. Station SW091: Variation of Pu-239,240 and Am-241 Activities with TSS

Relationship Between Radionuclides and Flow Rates for SW091

Results from station SW091, in contrast to station SW093, showed a weak relationship between total uranium and flow. These results are to be expected. Station SW091 monitors a small sub-basin with ephemeral flow. Because no baseflow exists at this location, the dilution of baseflow containing total uranium (as seen at station SW093) does not occur.

Plutonium and americium activities exhibit positive correlations with flow at station SW091 (see Figure B-8). This is expected based on trends observed at other gaging sites.

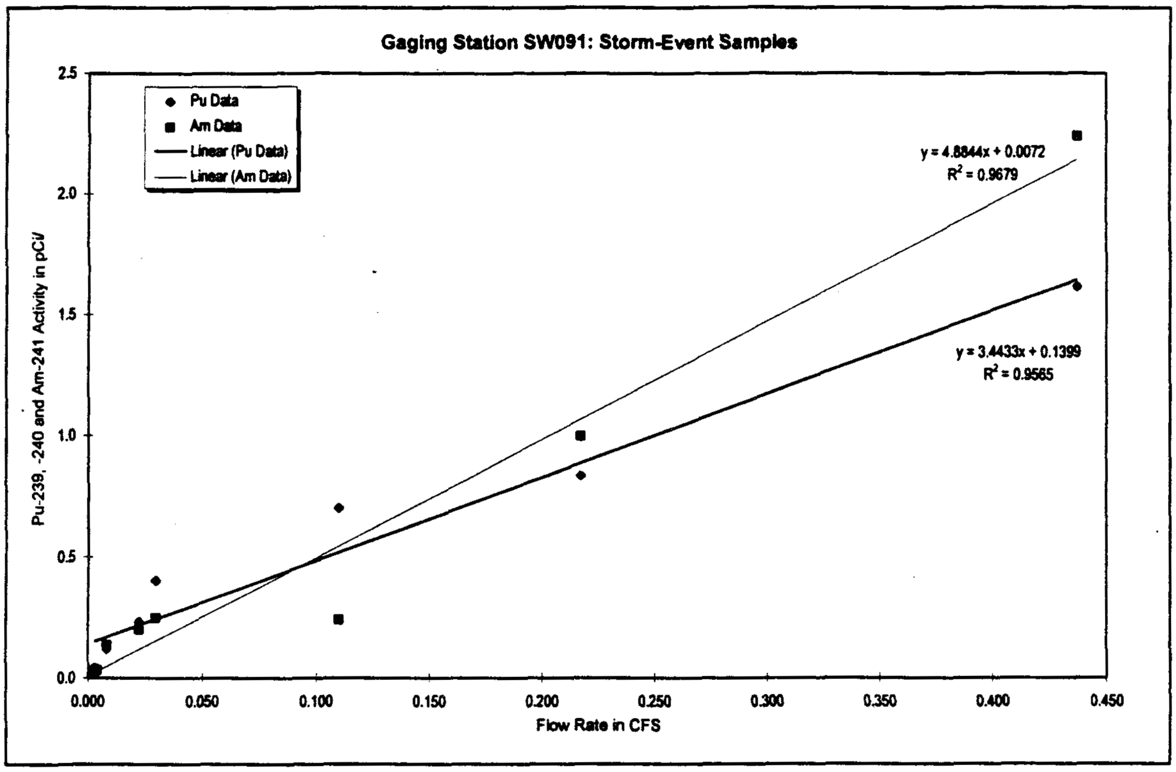


Figure B-8. Station SW091: Variation of Pu-239,240 and Am-241 Activities with Flow

B.2.2.7 Station SW022

Gaging Station SW022 is located at the inner east fence along Central Avenue Ditch monitoring storm-water runoff from the IA. Previously, storm-event samples were collected at SW022 as an IM/IRA Tier I location. Currently, SW022 is a NSD Location under RFCA.

General Water Quality Summary for SW022

SW022 shows activities of similar magnitude to GS10, and it represents approximately 34% of the surface-water runoff entering South Walnut Creek from the IA. Although SW022 measures runoff from the part of the Site where uranium use has historically occurred, it still represents a significant portion of the total plutonium and americium load to South Walnut Creek.

Relationship Between Radionuclides and Suspended Solids for SW022

Results of plutonium/americium and TSS from gaging station SW022 are similar to those collected from SW093. A positive trend for plutonium versus TSS is apparent; however, both plutonium and americium exhibit statistically poor correlations with TSS. As with SW093, the large size and variability of the drainage basin for SW022 (encompassing the entire south central portion of the IA) may account for the weak correlation between actinide activity and TSS.

Relationship Between Radionuclides and Flow Rates for SW022

Total uranium and flow exhibit no relationship at SW022. This is expected as flow at this site is ephemeral. Sources of groundwater with measurable levels of total uranium are not available for dilution by runoff; therefore, a negative correlation between total uranium and flow (as exists at station SW093) does not exist.

Plutonium and americium activities do not exhibit a good correlation with flow at station SW022.

B.2.2.8 Station GS10

Gaging station GS10 located along South Walnut Creek, upstream of the B-1 bypass, and monitors surface-water runoff from the IA. Storm-event samples were collected at GS10 as part of the Event-Related Surface-Water Monitoring Program and as a Tier I location under IA IM/IRA. Currently, GS10 serves as a POE and NSD Location under RFCA, collecting continuous flow-paced samples.

<u>General Water Quality Summary for GS10</u>

The values in Table B-2 indicate that there is a measurable increase in plutonium and americium in storm-event samples compared to continuous samples. This variation is expected if it is assumed that plutonium and americium are preferentially associated with particulate matter in the water column. Storm-event samples consist of grabs taken during high flow rates on rising limbs and therefore have higher TSS concentrations.

<u>Relationship Between Radionuclides and Suspended Solids for GS10</u>

Gaging station GS10 also monitors surface water from a fairly large drainage basin; however, dramatically better correlations for plutonium and americium versus TSS are observed from storm-event samples as compared to SW093 (Figure B-9). One possible explanation is that a significant actinide source exists near the GS10 sampling point. Such a source, downstream from the confluence of drainage sub-basins, would lead to regular contaminant mobilization with each event, regardless of precipitation distribution in the basin, because all water flowing to station GS10 would pass through the same contaminated source area. This theory is supported by the Site *Historical Release Report* (DOE, 1992), which indicates potential actinide sources may exist in the South Walnut Creek drainage, upstream from station GS10 and downstream from Building 991. Causes of these actinide sources are attributed to discharges of untreated laundry wastewater below Building 995 from 1953 to 1965 and resuspension of contaminated sediments resulting from drainage reconstruction activities from 1971 to 1973.

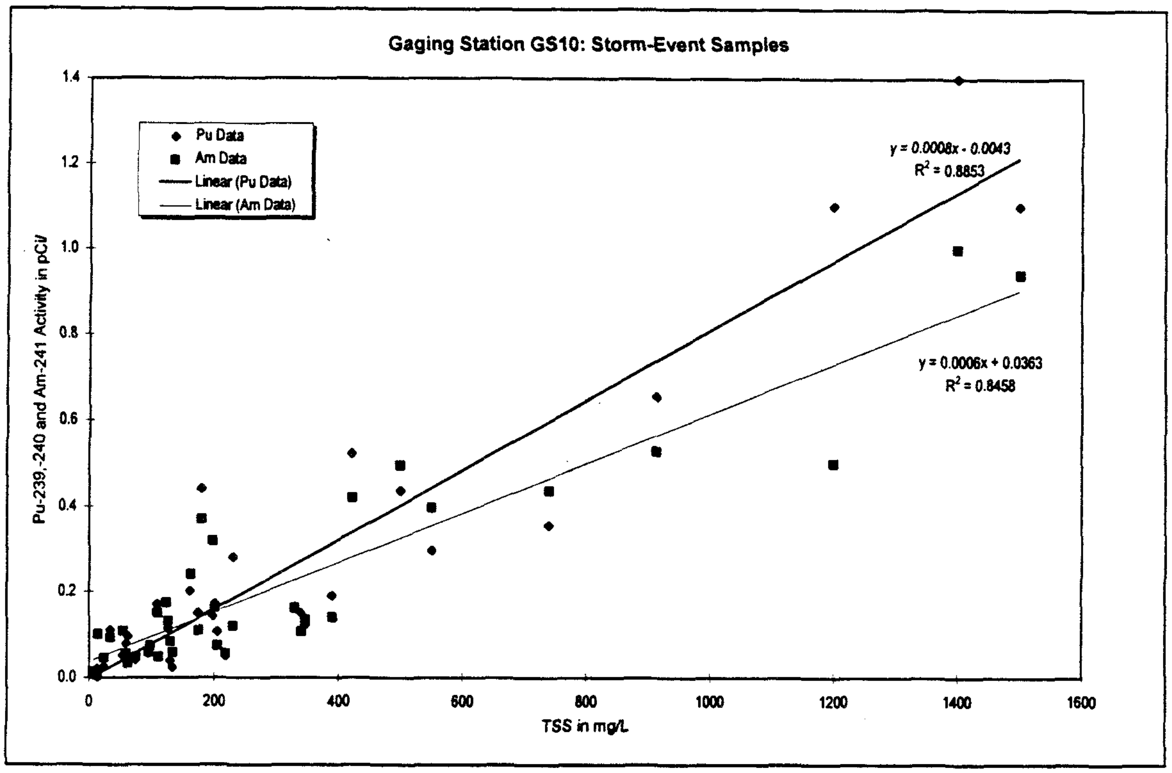


Figure B-9. Station GS10: Variation of Pu-239,240 and Am-241 Activities with TSS

<u>Relationship Between Radionuclides and Flow Rates for GS10</u>

No strong correlations were observed between total uranium and flow at station GS10. At low flow rates (less than 1 cfs), the average total uranium activity measured at GS10 is approximately 2 pCi/L. This contrasts with station SW093, where a strong, negative total uranium to flow relationship exists, and total uranium activity at low flow rates is approximately 4 pCi/L, or twice the activity of GS10. GS10 may not receive the ground water discharges, elevated in uranium that are apparently observed at SW093.

Plutonium and americium activities do not exhibit good correlations with flow at Station GS10. GS10 is in a relatively large basin receiving runoff from much of the IA. Variability in rainfall intensity and duration within the basin may be the cause of this poor relationship.

B.2.2.9 Station SW027

Gaging Station SW027 is located on the SID just upstream from Pond C-2 and monitoring surface-water runoff from the south part of the IA. Previously SW027 served as a gaging station for the Event-Related Surface-Water Monitoring Program and as a Tier I location under the IM/IRA, collecting storm-event samples. Currently, SW027 is a POE and NSD Location under RFCA, collecting continuous flow-paced samples.

General Water Quality Summary for SW027

The values in Table B-2 indicate there is a significant increase in plutonium and americium in storm-event samples at SW027 compared to continuous samples.
There is a measurable increase in total uranium at SW027 for storm events compared to continuous samples. This suggests that, for this basin, uranium may be preferentially associated with storm runoff, that it may indicate that the source of baseflow may be low in uranium, or that natural baseflow is minimal at this location. In fact, SW027 does not receive baseflow much of the year, and when it does, it is assumed that this baseflow (or a significant portion) originates as a domestic leak to the 400 Area stormwater collection system.

Relationship Between Radionuclides and Suspended Solids for SW027

Plutonium and americium activities from storm-event samples collected from gaging station SW027 show a general positive trend for americium versus TSS, with moderately good correlation. No significant relationship is observed between plutonium and TSS. Two factors may explain the lack of strong correlations. First, as discussed for monitoring results from other drainages, SW027 monitors a large basin, and the variability of sediment contamination across this drainage is documented (Efurd, et al., 1993). Second, TSS values from the storm water samples at SW027 are all fairly low and, as a result, comparison of variability is more difficult.

Relationship Between Radionuclides and Flow Rates for SW027

When analyzing data from storm events, none of the radionuclides exhibit a good relationship with flow at SW027. However, when the available data points (n = 4) of continuous flow-paced samples are examined, trends in radionuclide activity are observed. Total uranium trends to a negative relationship between activity and flow for continuous samples. Plutonium and americium trend to a positive relationship between activity and flow.

B.2.3 Summary Observations of Relationship Between Radionuclides and TSS

In general, the larger the basin, the more likely it is to exhibit greater variability in contaminant distribution as well as rainfall intensity distribution among events. These factors combine to produce variable exposure of runoff waters to contaminated soils. For instance, a large storm event may produce rainfall on those areas of the drainage basin with minimal radionuclide content in the soil, while another, similarly large storm event may produce rainfall primarily on areas in the basin with significant contamination. Both of these events of similar intensity might suspend similar concentrations of solids; however, the actinide levels in the samples would be quite different. Consequently, storm event samples from large basins may not be as readily comparable as those from smaller drainages.

Stations SW093, SW022, and SW027- The absence of a statistically significant relationship may be attributed to the relatively large size of the drainage basins tributary to these locations. In fact, the variability of sediment contamination across the drainage is documented (Efurd, et al., 1993).

Station GS10 - The relatively strong correlation for this upgradient of the SW057 location may be due to a significant actinide source near the GS10 sampling point. Such a source, downstream from the confluence of drainage sub-basins, would lead to regular contaminant mobilization with each event, regardless of where the precipitation occurred in the basin, because all water flowing to station GS10 would pass through a common contaminated source area. This explanation is supported by the Site *Historical Release Report* (DOE, 1992), which indicates potential actinide sources may exist in the South Walnut Creek drainage from historical discharges of untreated laundry wastewater below Building 995 from 1953 to 1965 and resuspension of contaminated sediments resulting from drainage reconstruction activities from 1971 to 1973 (DOE 1992).

Station SW091 - The smaller size of the basin may account for the improved correlation due to reduced variability of precipitation and runoff intensity. It should be noted that these correlations are based on relatively small data sets; consequently, the relationship is strongly influenced by the points of high activity.

Stations GS27 and GS28 - The strong correlations for these stations may be attributed to the small drainage areas (IA runoff sub-basins in the South Walnut Creek drainage, comprising less than 1 acre each) being monitored. However, it should be noted that only limited data sets are available for these locations (GS27, n = 13; GS28, n = 11), and the relationships are influenced by samples with high activity.

Analyses of sediment samples collected near GS27 may indicate that plutonium and americium are associated with a specific, more mobile fraction of the soil. Samples of sediment materials were taken from a drainage gutter on the south side of Building 884 and analyzed for actinide activities. These activities are detailed in section B.3.3.1.

These results do not show sufficient actinide content to account for the plutonium and americium levels observed in stormwater samples given the measured TSS concentrations. This apparent discrepancy may be due to radionuclides selectively associating with a specific fraction of the sediment which is essentially concentrated in the more easily mobilized TSS. This fraction may simply be the smaller particles which possess greater surface area for radionuclide attachment.

Stations GS21, GS22, GS24, and GS25 - Although these gaging stations all monitor fairly small basins and a better relationship with TSS might be expected, the lack of good correlations may be attributable to the overall low radionuclide activity in all the samples. Even the samples with the highest activities yielded actinide levels of similar magnitude to the reported analytical error. As a result, comparison of variation among the samples may not be meaningful.

B.2.4 Summary Observations of Relationship Between Radionuclides and Flow

SW093 - Monitoring results from station SW093 include storm-event and continuous flow-paced samples. This station receives near-continuous baseflow. These results indicate that runoff from storm events dilutes the total uranium activity in the baseflow and causes lowered activities at higher flow rates. This phenomenon may be caused by contaminated groundwater that supplies the baseflow and constitutes the primary source for total uranium observed in the surface water.

No relationship was observed for plutonium and americium activities as a function of flow at station SW093. This is to be expected as SW093 monitors a large, complex basin and no significant relationship was observed at this station for plutonium or americium activities and TSS.

SW091 - Station SW091 monitors a relatively small sub-basin with ephemeral flow. Because no baseflow exists at this site, the dilution of baseflow containing total uranium (as seen at station SW093) does not occur.

GS10 - Plutonium and americium activities do not exhibit good correlations with flow at Station GS10. GS10 is in a relatively large basin receiving runoff from much of the IA. Variability in rainfall intensity and duration within the basin may be the cause of this poor relationship.

SW022 - The lack of a relationship at SW022 (Pond B-5 influent) is expected seeing as flow at this site is ephemeral. Sources of groundwater with measurable levels of total uranium are not available for dilution by runoff; therefore, a negative correlation between total uranium and flow (as exists at station SW093) does not exist.

GS27 - This small IA sub-basin has no baseflow; therefore, the weak correlation between activity and flow is not surprising.

SW027 - The lack of good correlation is attributable to lack of data. The data set for this location is four. As a result, comparison of variation among the samples may not be meaningful.

GS21, GS22, GS24, and GS25 - These IA sub-basins (within the SID basin) are similar to GS27 with respect to size and lack of baseflow, therefore, the weak correlations are not surprising.

B.3 WATERSHED CHANGES AND RADIONUCLIDE TRANSPORT

Erosion control measures have been implemented at RFETS during water years 1996 and 1997 in an effort to stabilize and entrap soils and sediments likely to be transported from the watershed by storm water runoff. Control measures in the North Walnut Creek, South Walnut Creek, and South Interceptor Ditch drainage basins. Installation of these measures is based on studies which indicate that radionuclides may associate with solids suspended in storm water (DOE, 1996). Storm water data collected at the Site between 1991 and 1995 supports this conclusion (DOE, 1996). Based on these characteristics of radionuclides and storm water, removing particulate material from storm water runoff should reduce radionuclide loading to the water. Areas targeted for control measures were those locations identified as most likely to contribute material that could provide a transport mechanism for radionuclides in Site runoff.

B.3.1 Selection of Watershed Improvement Locations

Several sources of information, in conjunction with walk downs of RFETS, were used to determine locations where watershed improvements should be implemented. These information resources are listed below:

- Surface water monitoring data *from Event-Related Surface Water Monitoring Reports for Water Years* 1991 to 1993 (EG&G 1993, EG&G 1994);
- High purity germanium gamma surveys IA sediment quality data (ERM/ESE, 1994);
- IA soils data (RMRS, 1994); and
- *Historical Release Report* (DOE, 1992) information.

Items of concern noted during Site walk downs included the following items:

- Areas of concentrated fine sediments in drainage pathways;
- Areas which contribute large quantities of runoff (e.g., steep dirt roads, barren hillsides, roof drains, paved areas, and slopes needing revegetation);
- Erosion on surface radionuclide-contaminated IHSSs;
- Position of surface radionuclide-contaminated IHSSs in relation to storm water drainage pathways; and
- Overall erosional condition of storm drainage pathways.

Results of the various investigative surveys were used in conjunction with findings from RFETS walk downs to identify areas to target for watershed improvements. Specific types of improvement measures implemented are discussed in the following section.

B.3.2 Types of Watershed Improvements Implemented

Four types of watershed improvement measures have been implemented during water years 1996 and 1997. Two different hydraulically-applied erosion control products were utilized, silt fences were installed to capture sediments suspended in runoff, and overgrown vegetation was removed from the SID to improve the flow capacity in the channel. Brief descriptions are provided below for the two hydraulically-applied erosion control products.

SoilGuard® is a soil stabilizer and revegetation product hydraulically-applied at locations of RFETS targeted for erosion control where revegetation was beneficial, such as exposed dirt areas. This material, a combination of wood fibers mixed with a guar gum tackifier and fertilizers, is sprayed on by a certified contractor using a hydroseeding truck. The product can be used strictly as a soil stabilizer, without seed, or sprayed as a fixative on top of planted seeds. It dries within several hours to form a bonded fiber matrix, can withstand heavy rainfall while protecting the top layer of soil, and does not impact water quality. New vegetative growth can protrude through the matrix without disrupting the surrounding sealed area.

TopSeal® was applied at areas of RFETS targeted for erosion control where revegetation was not practical, such as dirt roads. This acrylic copolymer emulsion product is mixed with water and sprayed on using a water truck. It dries within several hours to seal and bind the soil together and does not pose a threat to water quality.

The effectiveness of these measures, where employed, is discussed in Section B.3.3.

B.3.3 Impacts of Watershed Changes on Radionuclide Transport

Two separate monitoring locations, GS27 (IA runoff) and SW027 (influent to Pond C-2), demonstrate how changes in the watershed impacts water quality. Monitoring results from these sites reflect the challenge in collecting an adequate number of samples at variable flow rates, once watershed improvements have been implemented, to properly assess whether or not improvements are reducing activity in runoff for high and low flows.

B.3.3.1 Impacts of Watershed Improvements on GS27

Station GS27 is of interest because it is a small basin draining less than 1 acre, and samples were collected before, during, and after improvements were implemented within the basin. Station GS27 was installed to monitor for possible impacts of the decontamination and decommissioning (D&D) at Building 889 (completed in July 1996) and of watershed improvements implemented in the basin. These watershed improvements included:

- Removing and drumming sediments, measured to contain 5 to 6 pCi/g of plutonium, accumulated on the asphalt south of Building 884 (completed July 1996); and
- Applying TopSeal® on the exposed dirt areas south of Building 884 (completed October 1996).

The majority of post-improvement samples were collected at low flow rates. Pu-239/240 and Am-241 activities in samples collected at GS27 before and after the initial improvements were implemented are shown in Figure B-10.

Although these data points indicate actinide activities as low or lower, for a given flow, than prior to the improvements, it is impossible to extrapolate this data to define the impact on water quality of the control measures when higher flows occur.

More data at higher flow rates needs to be collected before conclusions can be drawn. Station GS27 remains on-line to fill this data gap by collecting samples when a higher flow rate does occur.

Samples of a secondary deposit of sediment materials were collected from pavement on the south side of Building 884 and analyzed for actinide activities. These results are presented in Table B-4.

Table B-4. Analytical Results from Sediment Samples near Building 884

Sample Number	Pu-239, 240 (pCi/g)	Am-241 (pCi/g)
SD01001JE	6.602 ±0.263	1.269 ±0.133
SD01002JE	5.717 ±0.248	1.833 ±0.175
SD01003JE	5.672 ±0.232	1.453 ±0.150
SD01003JE- DUPLICATE	5.523 ±0.231	1.850 ±0.200

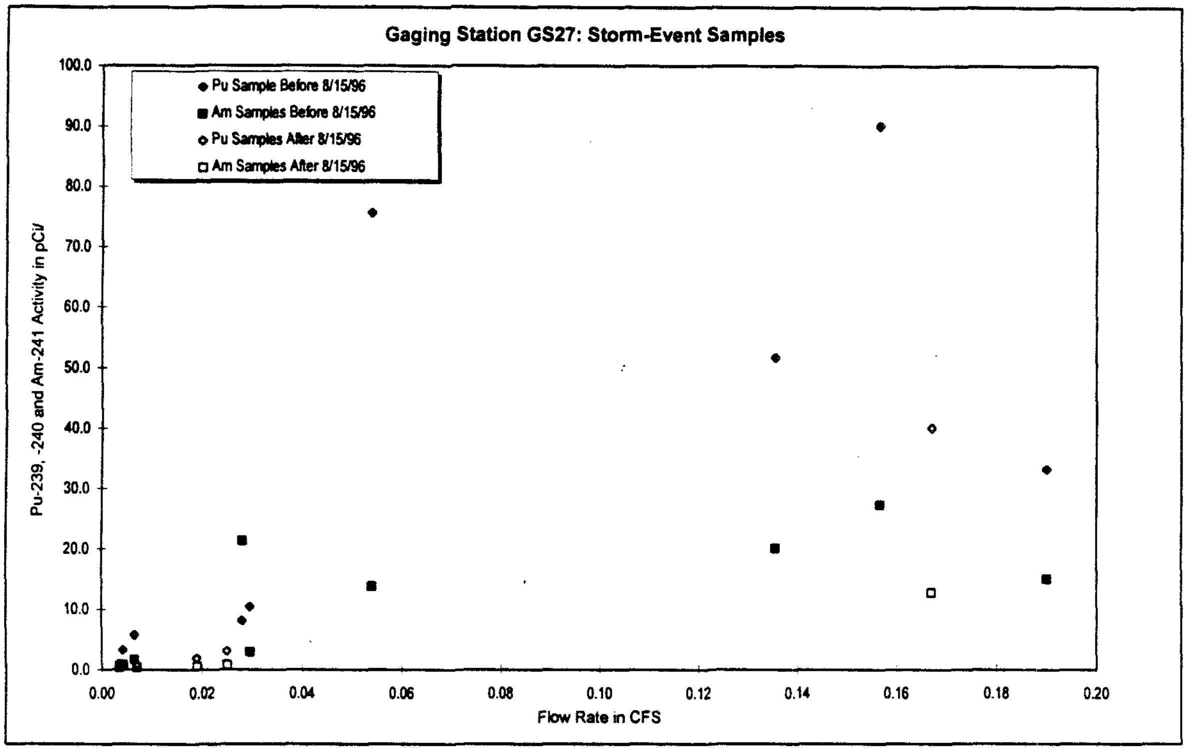


Figure B-10. Station GS27: Pu-239,240 and Am-241 Activities Before and After Implementation of Watershed Improvements

Although these results do not show sufficient actinide content to account for the plutonium and americium levels observed in storm samples given the measured TSS concentrations.

GS27 was installed to monitor for increased actinide transport during the D&D of Building 889.

B.3.3.2 Impacts of Watershed Improvements on SW027

Samples collected since controls were implemented indicate reduced plutonium and americium activity to flow ratios at Station SW027 since the time when improvements were first implemented in this basin (Figure B-11). A dirt road running south down the hill from the 903 Pad, toward Pond C-1, was revegetated during the Summer of 1996 and treated with SoilGuard®. In addition, dirt roads encircling the 903 Pad were treated with TopSeal® during the past year. However, it should be noted that the sampling protocol at station SW027 changed from storm-event sampling to continuous flow-paced sampling as a result of RFCA requirements, in the midst of the improvements being implemented; therefore results have to be reviewed accordingly (storm-event samples generally have higher activities than continuos flow-paced samples). However, results of storm-event samples also indicate reduced radionuclide loading following the implementation of improvement measures.

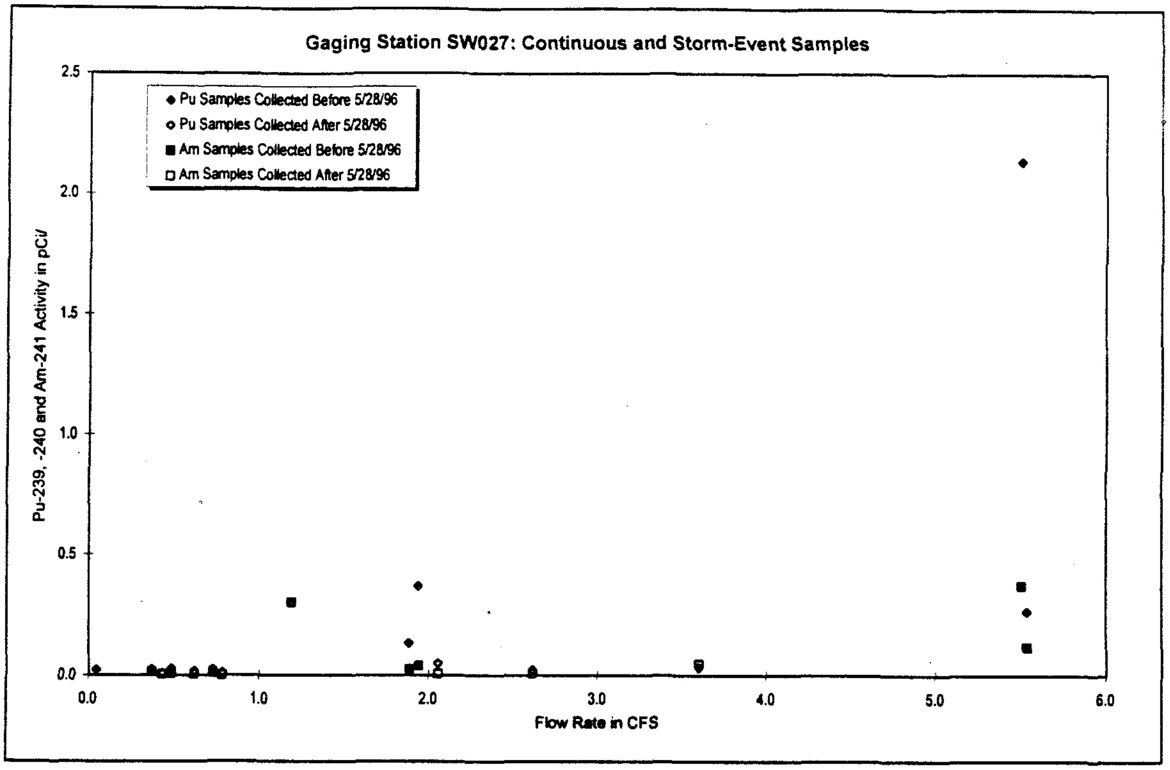


Figure B-11: Station SW027: Pu-239,240 and Am-241 Activities Before and After Implementation of Watershed Improvements

B.4 SUMMARY OF FINDINGS

A summary of findings for both general and location-specific transport are discussed. It was assumed that if a relationship between radionuclide activity and TSS holds for a given location, then radionuclide activity may be correlated with flow rate as well. Although these relationships might be anticipated for most sampling locations, determination of whether this relationship exists may be difficult to assess for several reasons:

- A TSS (mg/L) to radionuclide (pCi/L) relationship assumes that the activity is proportional to the mass of solids independent of available surface area or particle composition. However, radionuclide association involves the physiochemical properties of the particles themselves, and is more complex than a simple pCi/g relationship.

- Source areas in any particular drainage may have unique physiochemical characteristics and contamination levels may vary within a drainage making the water quality characteristics of runoff from a sub-drainage would be unique. When precipitation events do not occur uniformly over an area (especially for large drainages), the water quality characteristics measured at a monitoring location will depend on the origination of that runoff. In fact, there may be several, or many, concurrent relationships that could be established for a given location.

- Since a given drainage is continually changing, either through natural erosion or anthropogenically through D&D or construction activities, there may not be time to collect sufficient information to determine one relationship before it is superseded by another.

Plutonium and americium transport is related to both TSS and flow rate. In general, sampling sites in small drainages provide more distinct, positive correlations compared to sites located in larger basins. The correlation is also stronger in drainages that collect runoff from areas with widespread, surface radionuclide contamination. Results from station GS10, a large basin capturing runoff from roughly two thirds of the IA, represent the exception to this observation by exhibiting a strong correlation between plutonium/americium activity and TSS.

A positive correlation is observed between plutonium and americium activity and flow rate across the Site. As with the plutonium/americium relationship to TSS, the plutonium/americium correlation with flow is markedly better for smaller drainages. Again, this may reflect diminished contaminant level and rainfall variability inherent in smaller basin areas.

The positive correlations of activity with both TSS and flow suggests that transport of plutonium and americium is facilitated by dislocation and transport of suspended particles whose suspension is a function of flow rate and precipitation intensity.

Despite mobilization of plutonium and americium detected during storm events in storm event samples, pond effluent sampling indicates the pond system performs well to attenuate and settle contaminants in storm water prior to discharge off-site. Contaminant levels measured in storm water flowing from the ponds are typically decreased at least 10-fold from that of influent levels.

B.5 REFERENCES

DOE, 1992, Historical Release Report for the Rocky Flats Plant, Rocky Flats Plant Site, Environmental Restoration Program, Golden, Colorado, June, 1992.

DOE, 1996, Pond Operations Plan: Revision 2, Rocky Flats Environmental Technology Site, RF/ER-96-0014.UN, Golden, Colorado, September, 1996.

Efurd, D.W., Rokop, D.J., and Perrin, R.E., 1993. Characterization of the Radioactivity in Surface-Waters and Sediments Collected at the Rocky Flats Facility, Los Alamos National Laboratory, LA-UR-93-4373.

EG&G, 1993, Event-Related Surface Water Monitoring Report, Rocky Flats Plant: Water Years 1991 and 1992, EG&G Rocky Flats, Inc., Golden, Colorado, November, 1993.

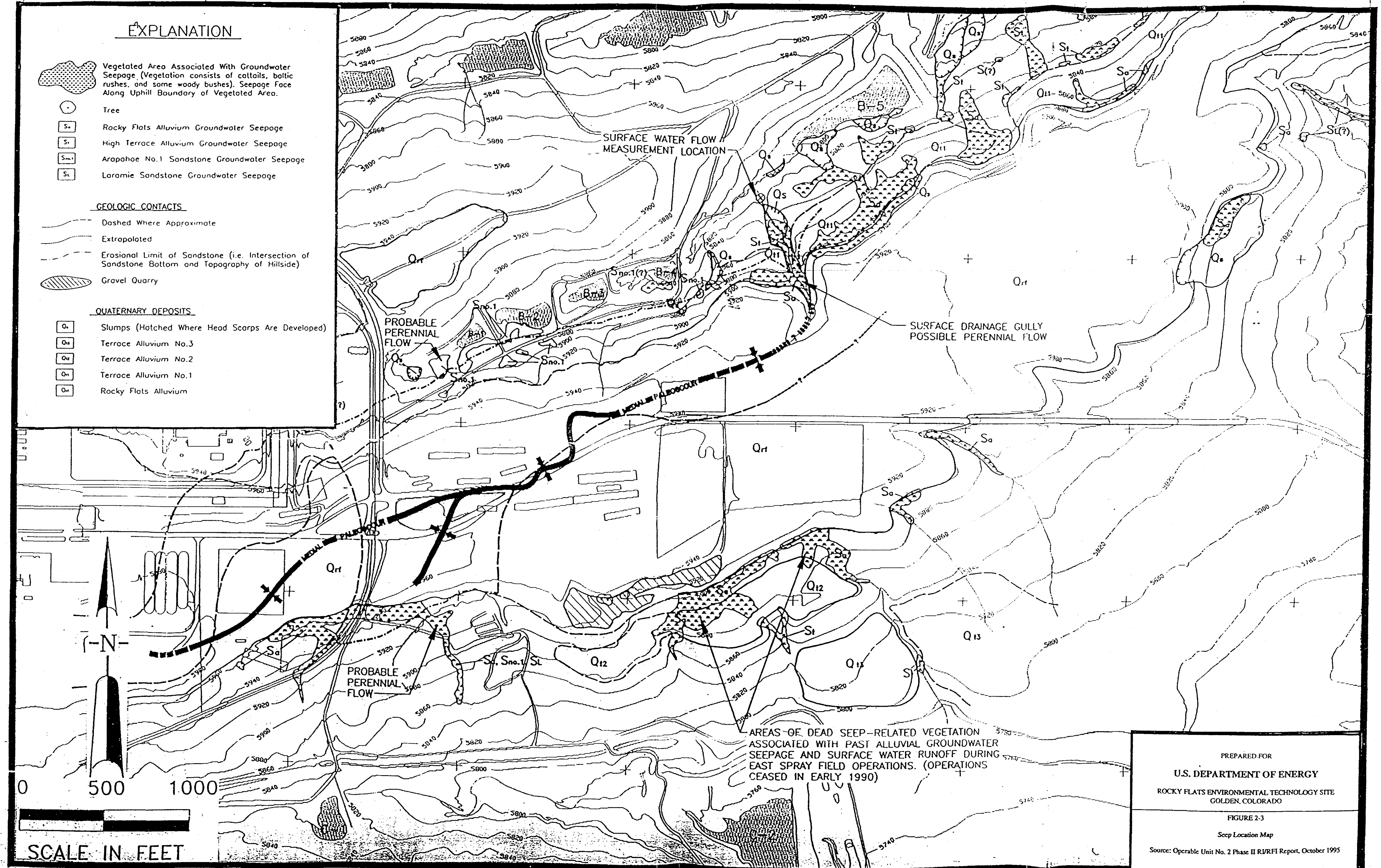
EG&G, 1994, Event-Related Surface Water Monitoring Report, Rocky Flats Environmental Technology Site: Water Year 1993, EG&G Rocky Flats, Inc., Golden, Colorado, November, 1994.

EG&G, 1995, Event-Related Surface Water Monitoring Report, Rocky Flats Environmental Technology Site: Water Year 1994, EG&G Rocky Flats, Inc., Golden, Colorado, November, 1995.

Kaiser-Hill, 1997, Integrated Monitoring Plan, Revision 1, Rocky Flats Environmental Technology Site, Kaiser-Hill Company, L.L.C., June, 1997.

APPENDIX C

OVERSIZED FIGURES



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U.S. DEPARTMENT OF ENERGY

ROCKY FLATS ENVIRONMENTAL TECHNOLOGY SITE
GOLDEN, COLORADO

FIGURE 2-3

Seep Location Map

Source: Operable Unit No. 2 Phase II RI/RFI Report, October 1995

Figure 2-4

RFETS
Drainage Features

EXPLANATION

Standard Map Features

- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences
- Rocky Flats boundary
- Paved roads
- Dirt roads

DATA SOURCE:
Buildings, roads, and fences provided by Facilities Engr., EG&G Rocky Flats, Inc. - 1991.
Hydrology provided by USGS - (date unknown)

Scale = 1 : 21330
1 inch represents approximately 1778 feet

500 0 1000 2000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

U.S. Department of Energy
Rocky Flats Environmental Technology Site

Prepared by:

Rocky Mountain
Remediation Services, L.L.C.
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MAP ID: 97-0141 July 24, 1997

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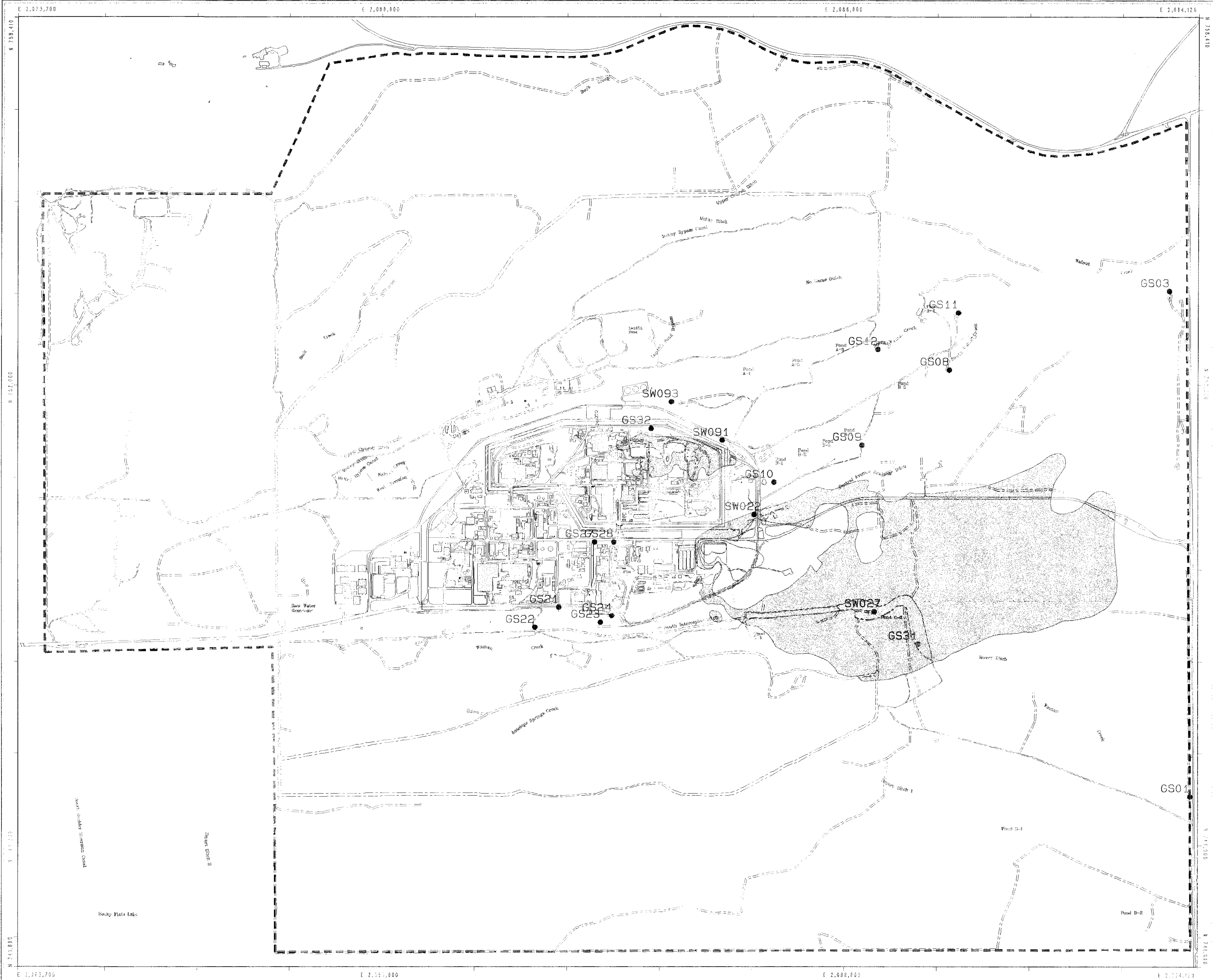

Figure 4-1
Distribution of Americium-241 in Surface Soil

EXPLANATION

- Less than 1 pCi/g
- 1 pCi/g or greater but less than 10 pCi/g
- 10 pCi/g or greater but less than 100 pCi/g
- 100 pCi/g or greater but less than 1000 pCi/g
- 1000 pCi/g or greater
- Selected SW Monitoring Stations

Standard Map Features

- Buildings & other structures
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences
- Rocky Flats boundary
- Paved roads
- Dirt roads

DATA SOURCE: Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

Scale = 1 : 21330
1 inch represents approximately 1778 feet

500 0 1000 2000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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MAP ID: 97-0130

August 15, 1997

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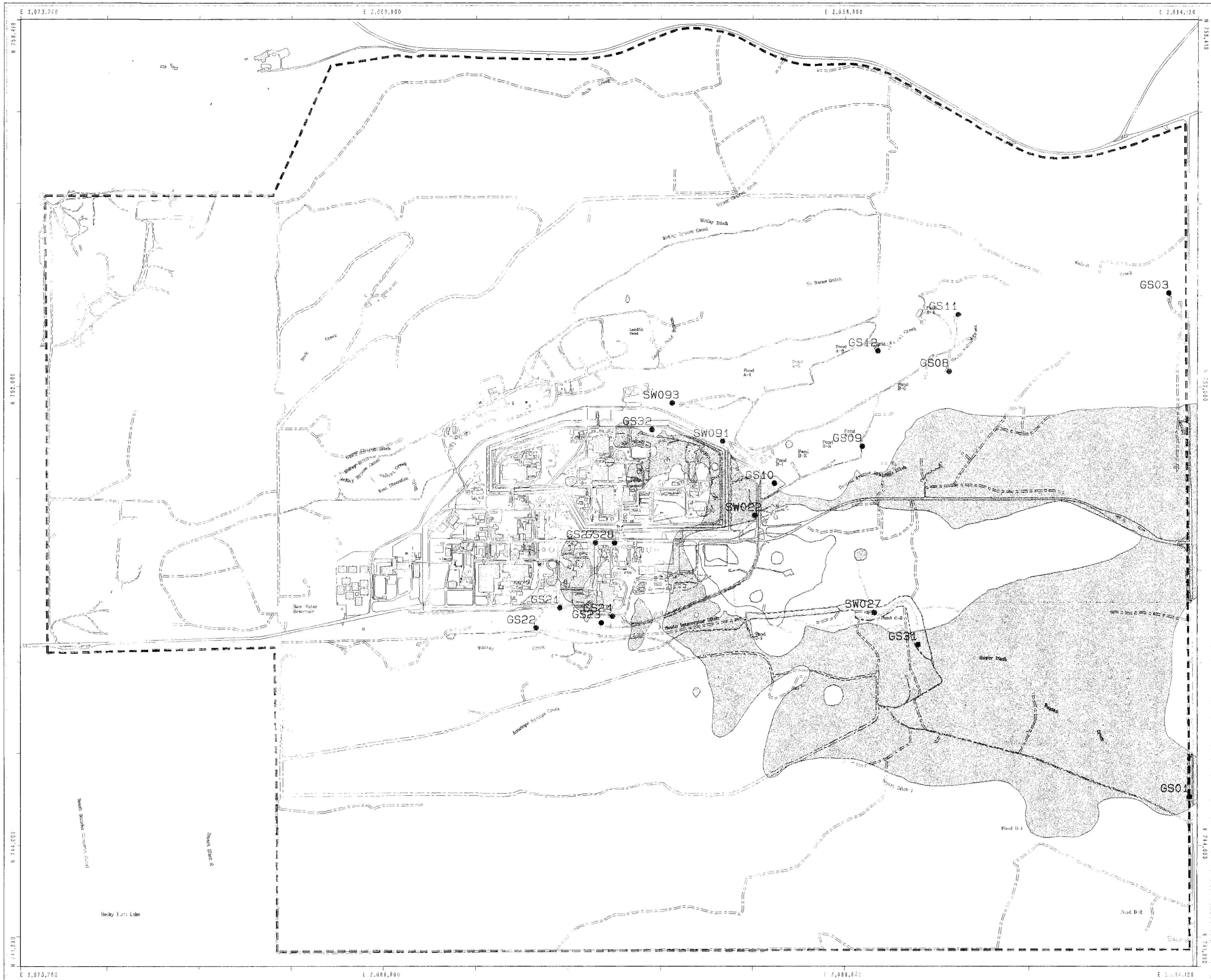

Figure 4-2
Distribution of Plutoniun-239/240 in Surface Soil

EXPLANATION

- Less than 1 pCi/g
- 1 pCi/g or greater but less than 10 pCi/g
- 10 pCi/g or greater but less than 100 pCi/g
- 100 pCi/g or greater but less than 1000 pCi/g
- 1000 pCi/g or greater
- Selected SW Monitoring Stations

Standard Map Features

- Buildings & other structures
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences
- Rocky Flats boundary
- Paved roads
- Dirt roads

DATA SOURCE: Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

Scale = 1 : 21330
1 inch represents approximately 1778 feet

500 0 1000 2000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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MAP ID: 97-0130

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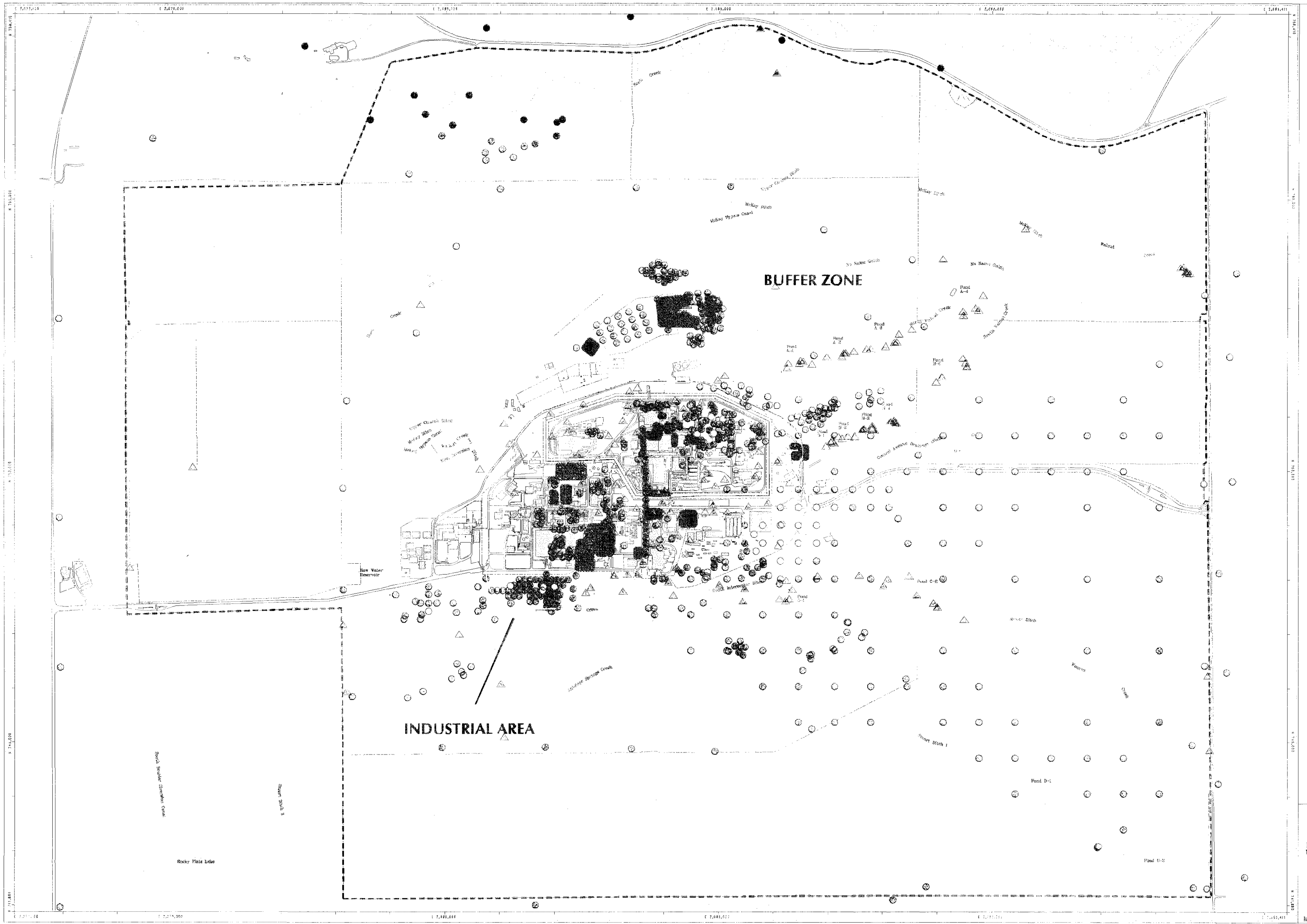

Figure 4-3

Surface Soil and Sediment Sampling Locations

Plutonium, Uranium & Americium Activities by Action Level

Legend

Action Level - Sum of Ratios

- Below Tier II Action Levels
- Above Tier II but below Tier I Action Levels
- Above Tier I Action Levels
- Surface soil location that has been removed (remediated)

Sampling Locations

- Surface Soil Samples
- Sediment Samples

Standard Map Features

- Buildings or other structures
- Solar evaporation ponds
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences and other barriers
- Rocky Flats boundary
- Paved roads

DATA SOURCE:
Action level ratios were calculated by dividing analytical results from RFEDS database by the appropriate action level from RFCA, attachment 5. The ratios for each isotope were then summed for each location to produce a sum of ratios that were then plotted.
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas.
Digitized from the orthophotographs. 1/95

Scale = 1 : 22540
1 inch represents approximately 1878 feet

500 0 1000 2000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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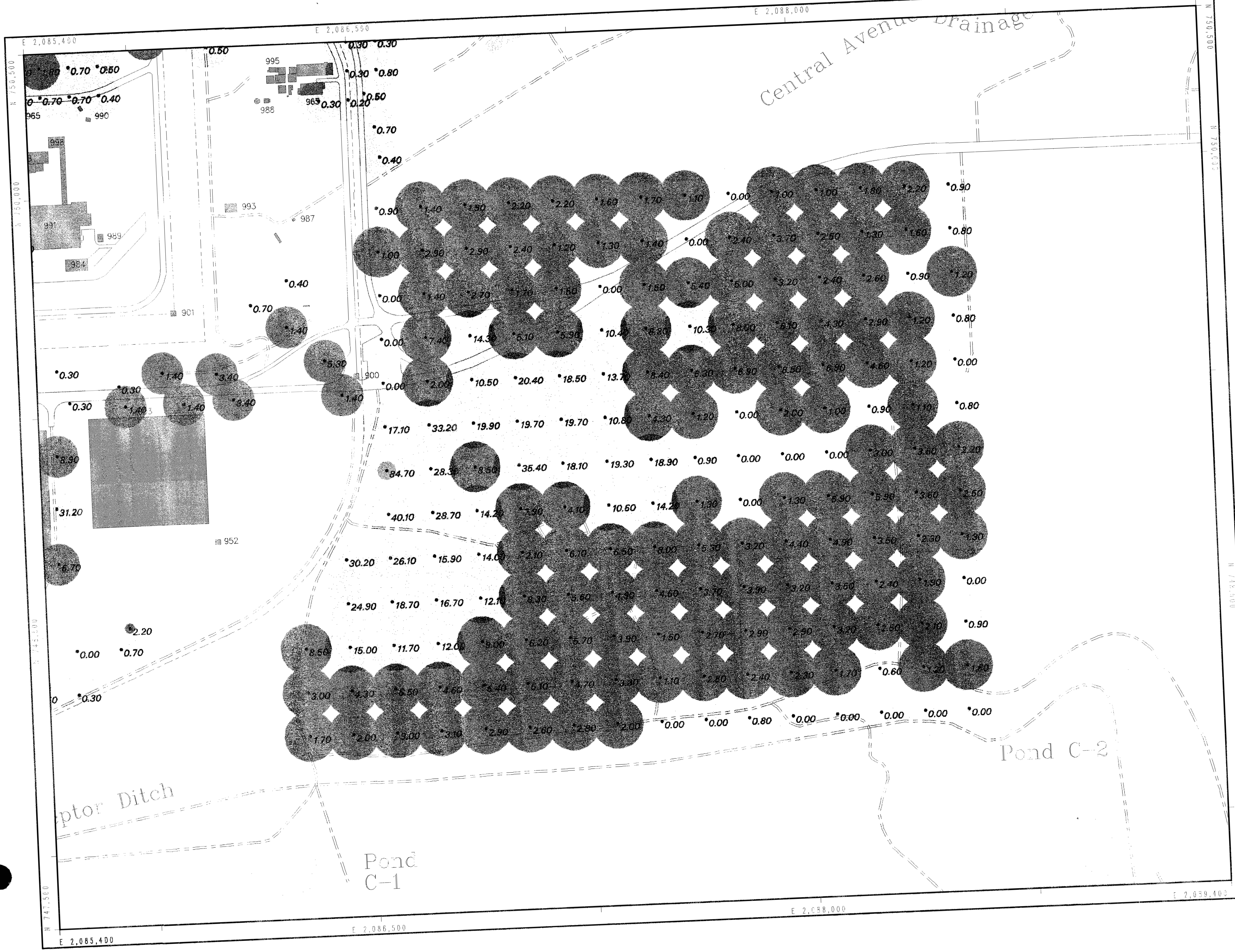
MAP ID: 97-0111-88

September 17, 1997

/gis2/projects/fy97/97-0111/mapaml/ss-sd-map.aml

Figure 4-4

HPGe Data for Am-241 pCi/g (for a Field of View of 150 feet)



HPGe Data Ranges pCi/g

- 0.0 - 0.1
- 0.1 - 1
- 1 - 10
- 10 - 100
- 100 - 1000
- 1000 - 10000

Standard Map Features--

- Buildings or other structures
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences
- Rocky Flats boundary
- Paved roads
- Dirt roads

DATA SOURCE:
HPGe data from Ron Reimen, Gamma Survey Group, Safeguard Measurements, EG&G Rocky Flats, Inc. June 1994
Buildings, roads, and fences provided by Facilities Engr., EG&G Rocky Flats, Inc. - 1991.
Hydrology provided by USGS - (date unknown)

150 0 300ft

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July 16, 1997

MAP ID: HPGe-OU2

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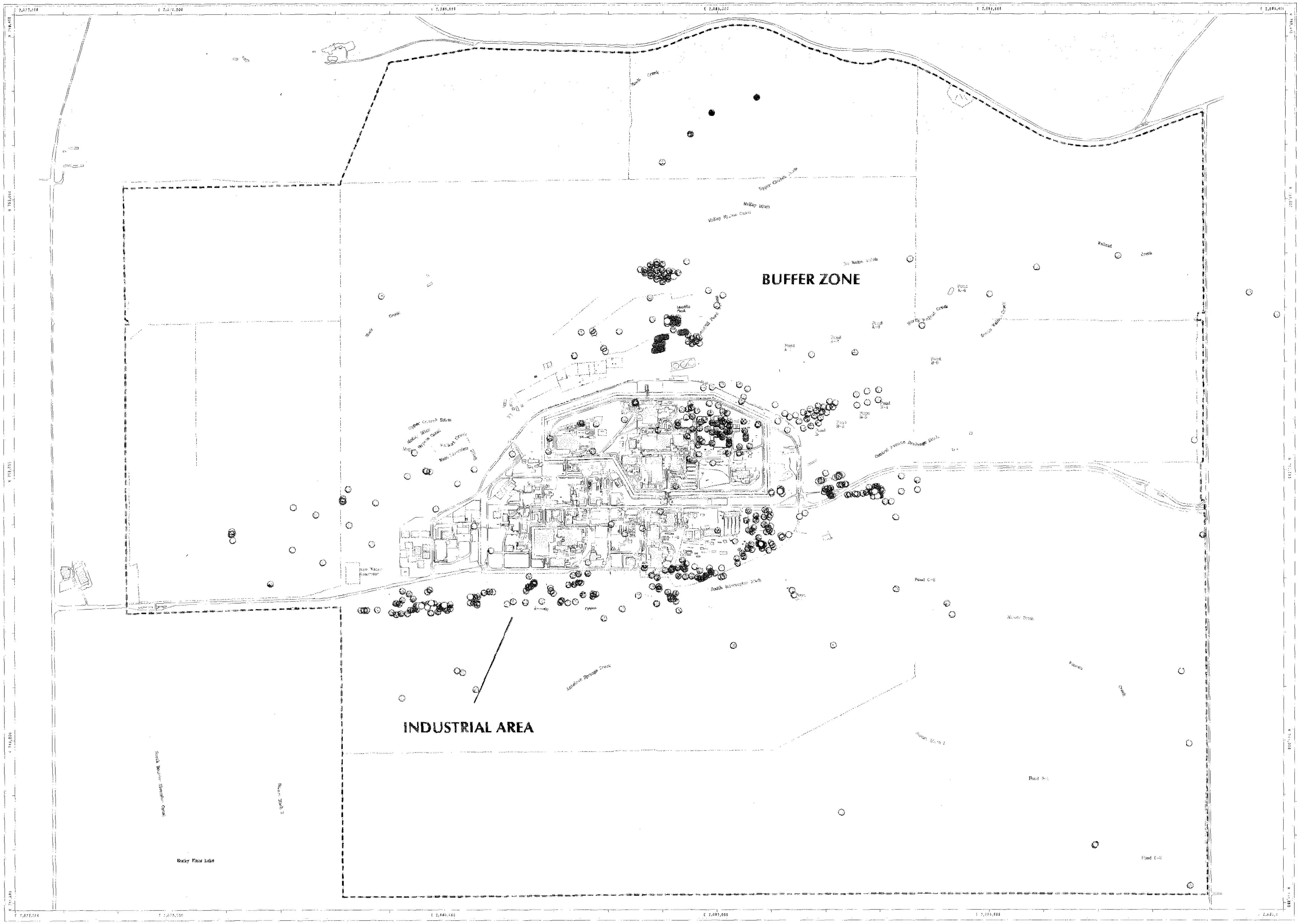

Figure 4-5

Subsurface Soil Sampling Locations
(Borehole & Groundwater Well)

Plutonium, Uranium & Americium Activities by Action Level

Legend

Action Level - Sum of Ratios

- Below Tier II Action Levels
- Above Tier II but below Tier I Action Levels
- Above Tier I Action Levels
- Borehole or Well location that has been removed (remediated)

Standard Map Features

- Buildings or other structures
- Solar evaporation ponds
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences and other barriers
- Rocky Flats boundary
- Paved roads

DATA SOURCE:
Action level ratios were calculated by dividing analytical results from RFEDS database by the appropriate action level from RFCA, attachment 5. The ratios for each isotope were then summed for each location to produce a sum of ratios that were then plotted.
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas.
Digitized from the orthophotographs. 1/95

Scale = 1 : 22540
1 inch represents approximately 1878 feet

500 0 1000 2000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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MAP ID: 97-0111-BH August 14, 1997

/home/rb1487b/projects/97-0111/mapam l/bh.aml

Figure 4-6

Soil Pit Locations

EXPLANATION

Soil Pit Location

Standard Map Features

Buildings & other structures

Lakes and ponds

Streams, ditches, or other drainage features

Fences

Rocky Flats boundary

Paved roads

Dirt roads

DATA SOURCE: Buildings, roads, and fences provided by Facilities Engr., EG&G Rocky Flats, Inc. - 1991. Hydrology provided by USGS - (date unknown)

Scale = 1 : 21330
1 inch represents approximately 1778 feet

500 0 1000 2000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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Golden, CO 80402-0464

MAP ID: 97-0130

July 03, 1997

/gis1/data/ftp-map-am/e/97-0180/soilbt.aml

Figure 4-9
Distribution of Uranium-233/234 in Surface Soil

EXPLANATION

- Less than 10 pCi/g
- 10 pCi/g or greater but less than 100 pCi/g
- 100 pCi/g or greater but less than 1000 pCi/g
- 1000 pCi/g or greater
- Selected SW Monitoring Stations

Standard Map Features

- Buildings & other structures
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences
- Rocky Flats boundary
- Paved roads
- Dirt roads

DATA SOURCE:
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the othophotographs. 1/95

Scale = 1 : 21330
1 inch represents approximately 1778 feet

500 0 1000 2000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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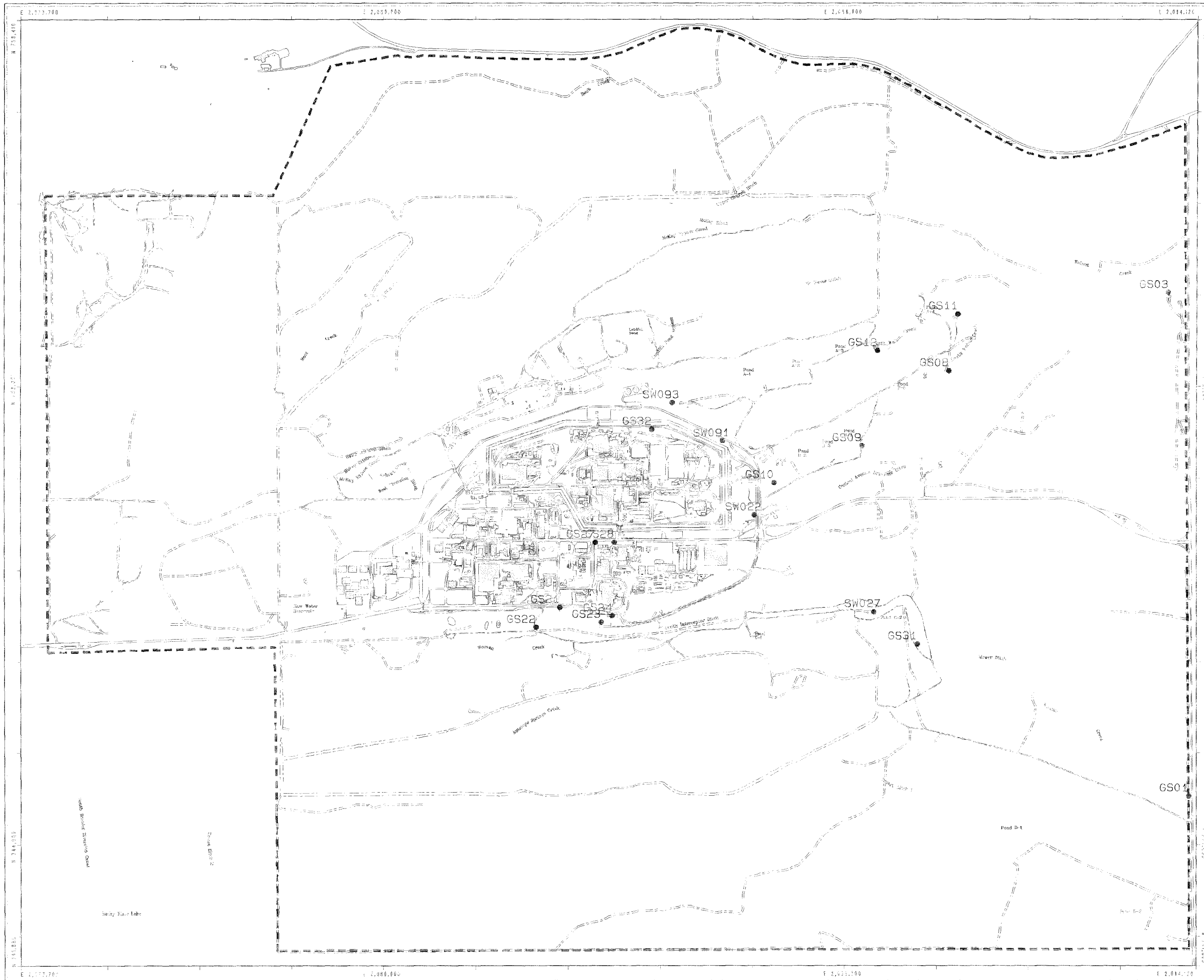
MAP ID: 97-0130

August 15, 1997

/gis8/projects/fy97/97-0130/sxu-233.aml

Figure 4-10
Distribution of Uranium-235 in Surface Soil



EXPLANATION

- Less than 10 pCi/g
- 10 pCi/g or greater but less than 100 pCi/g
- 100 pCi/g or greater but less than 1000 pCi/g
- 1000 pCi/g or greater
- Selected SW Monitoring Stations

Standard Map Features

- Buildings & other structures
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences
- Rocky Flats boundary
- Paved roads
- Dirt roads

DATA SOURCE:
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs, 1/95

Scale = 1 : 21330
1 inch represents approximately 1778 feet

500 0 1000 2000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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MAP ID: 97-0130 August 15, 1997

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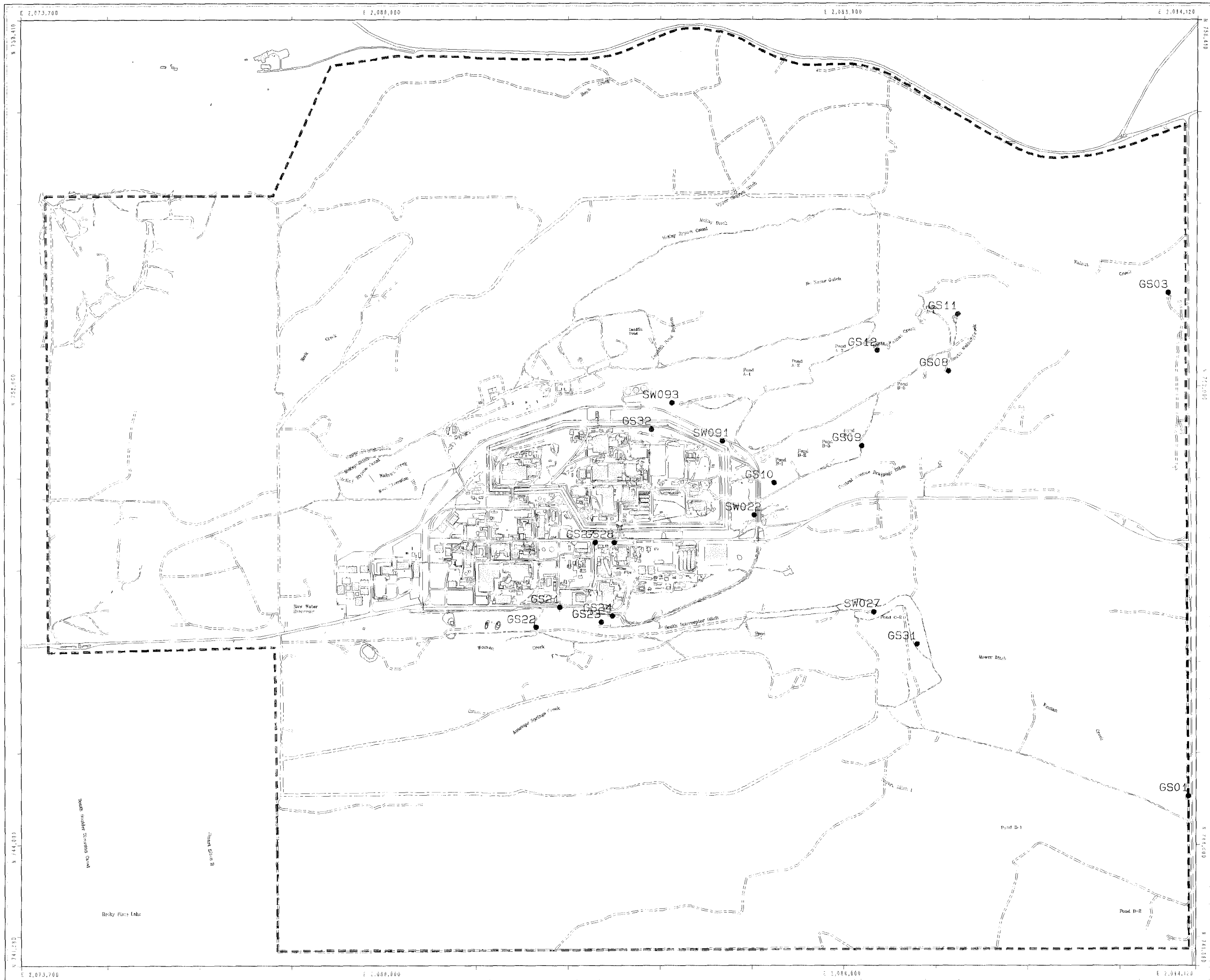

Figure 4-11
Distribution of Uranium-238 in Surface Soil

EXPLANATION

- Less than 10 pCi/g
- 10 pCi/g or greater but less than 100 pCi/g
- 100 pCi/g or greater but less than 1000 pCi/g
- 1000 pCi/g or greater
- Selected SW Monitoring Stations

Standard Map Features

- Buildings & other structures
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences
- Rocky Flats boundary
- Paved roads
- Dirt roads

DATA SOURCE: Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

Scale = 1 : 21330
1 inch represents approximately 1778 feet

500 0 1000 2000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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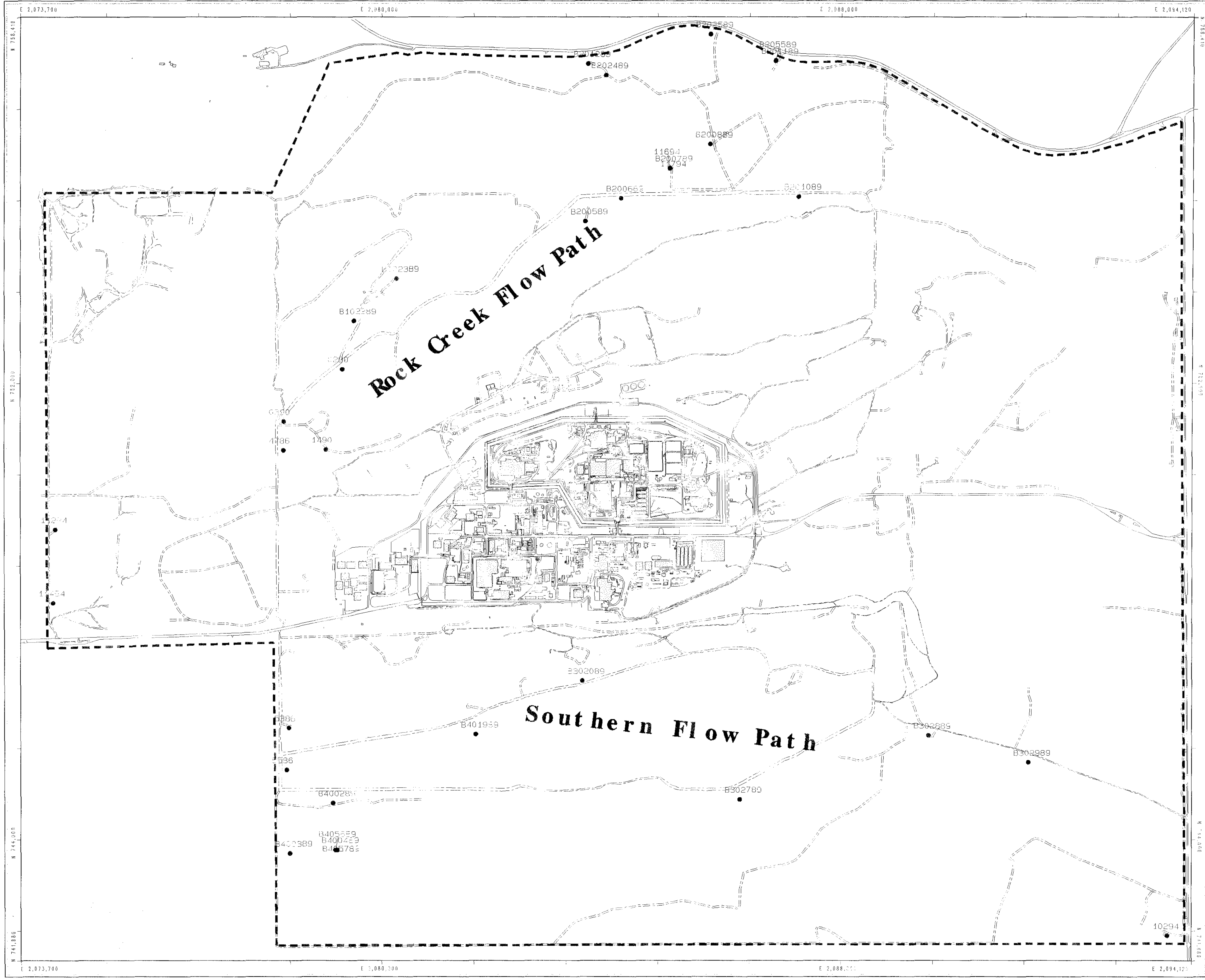

Figure 5-1

BackGround Groundwater Monitoring Wells and Flow Paths

EXPLANATION

● Background Groundwater Monitoring Wells

Standard Map Features

- Buildings & other structures
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences
- Rocky Flats boundary
- Paved roads
- Dirt roads

DATA SOURCE: Buildings, roads, and fences provided by Facilities Engr., EG&G Rocky Flats, Inc. - 1991. Hydrology provided by USGS - (date unknown)

Scale = 1 : 21330
1 inch represents approximately 1778 feet

500 0 1000 2000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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MAP ID: 97-0130 July 23, 1997

/gis1/data/rfp-map-em/97-0130/bgwells.aml

Figure 5-2
Unfiltered Plutonium 239/240 in Alluvial Groundwater 1991-1995

Plutonium 239/240 Activity-Concentration (pCi/l)

- 0.0 - 0.05
- 0.05 - 0.16
- 0.16 - 0.5
- 0.5 - 1.0
- > 1.0

- Alluvium Wells
- Bedrock Wells

BACKGROUND BENCHMARK = 0.047 pCi/L

Standard Map Features

- Buildings or other structures
- Solar evaporation ponds
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences
- Rocky Flats boundary
- Paved roads
- Dirt roads

DATA SOURCE:
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs, 1/95

Scale = 1 : 21330
1 inch represents approximately 1778 feet

500 0 1000 2000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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Golden, CO 80402-0464

MAP ID: 97-0133 September 29, 1997

/gis2/projects/fy97/97-0133/rads_11x17.aml

Figure 5-3
Unfiltered Americium 241 in Alluvial Groundwater 1991-1995

Americium 241 Activity-Concentration (pCi/l)

- 0.0 - 0.04
- 0.04 - 0.15
- 0.15 - 1.0
- 1.0 - 5.0
- > 5.0

- Alluvium Wells
- Bedrock Wells

BACKGROUND BENCHMARK = 0.036 pCi/L

Standard Map Features

- Buildings or other structures
- Solar evaporation ponds
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences
- Rocky Flats boundary
- Paved roads
- Dirt roads

DATA SOURCE: Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs, 1/95

Scale = 1 : 21330
1 inch represents approximately 1778 feet

500 0 1000 2000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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Golden, CO 80402-0464

MAP ID: 97-0133

September 26, 1997

/gis2/projects/fy97/97-0133/rads_11x17.aml


Figure 5-5
Filtered Uranium 233/234
in Alluvial Groundwater
1991-1995
Uranium 233/234 Activity-Concentration (pCi/l)
0 - 1
1 - 5
5 - 40
40 - 60.7
60.7 - 100
> 100
RFCA wells not sampled in 1996
Alluvium Wells
Bedrock Wells
Background Benchmark = 60.7 pCi/L
Action Level = 1.07 pCi/L
Standard Map Features
Buildings or other structures
Solar evaporation ponds
Lakes and ponds
Streams, ditches, or other drainage features
Fences
Rocky Flats boundary
Paved roads
Dirt roads
DATA SOURCE:
Scale = 1 : 21330
1 inch represents approximately 1778 feet
500 0 1000 2000 ft
State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27
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Prepared by:
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Geographic Information Systems Group
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Golden, CO 80402-0464
MAP ID: 97-0133
September 26, 1997

Figure 5-6
Filtered Uranium 235
in Alluvial Groundwater
1991-1995
Uranium 235 Activity-Concentration (pCi/l)
0 - 0.1
0.1 - 0.5
0.5 - 1.0
1.0 - 1.79
1.79 - 5
> 5
RFCA wells not sampled in 1996
Alluvium Wells
Bedrock Wells
Background Benchmark = 1.79 pCi/L
Action Level = 1.01
Standard Map Features
Buildings or other structures
Solar evaporation ponds
Lakes and ponds
Streams, ditches, or other drainage features
Fences
Rocky Flats boundary
Paved roads
Dirt roads
DATA SOURCE:
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas.
Digitized from the orthophotographs. 1/95
Scale = 1 : 21330
1 inch represents approximately 1778 feet
500 0 1000 2000 ft
State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27
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P.O. Box 464
Golden, CO 80402-0464
MAP ID: 97-0133
September 26, 1997
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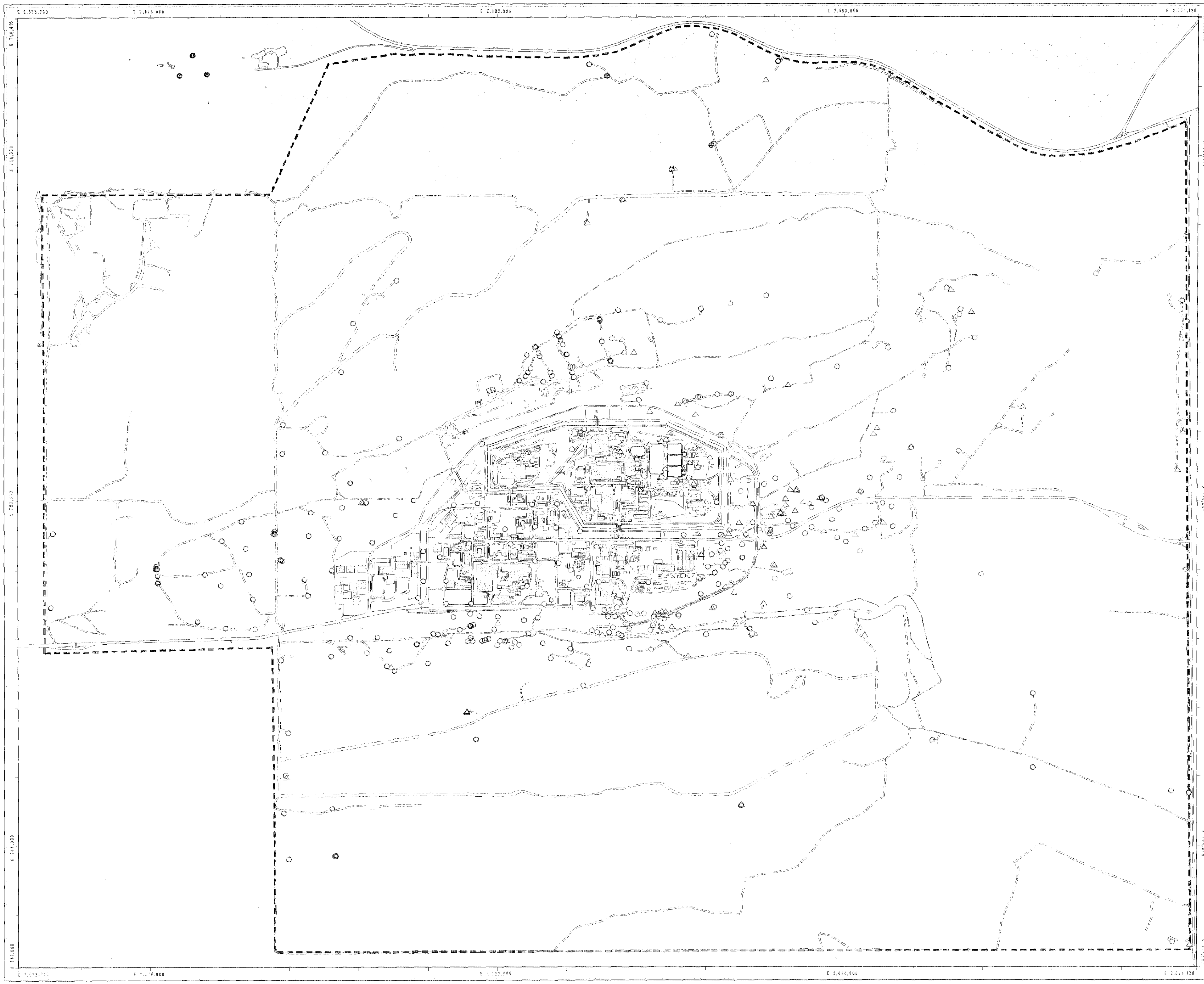

Figure 5-7
Filtered Uranium 238 in Alluvial Groundwater 1991-1995

Uranium 238 Activity-Concentration (pCi/l)

- 0 - 0.77
- 0.77 - 5
- 5 - 10
- 10 - 41.8
- 41.8 - 100
- > 100
- RFCA wells not sampled in 1996
- Alluvium Wells
- Bedrock Wells

Background Benchmark = 41.8 pCi/L
Action Level = 0.767 pCi/

Standard Map Features

- Buildings or other structures
- Solar evaporation ponds
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences
- Rocky Flats boundary
- Paved roads
- Dirt roads

DATA SOURCE:
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the othophotographs. 1/95

Scale = 1 : 21330
1 inch represents approximately 1778 feet

500 0 1000 2000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

U.S. Department of Energy
Rocky Flats Environmental Technology Site

Prepared by:

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MAP ID: 97-0133 September 26, 1997

/gis2/projects/fy97/97-0133/rads_11x17.aml

Figure 6-1

Selected Surface Water Monitoring Stations

EXPLANATION

- New Source Detection
- Points of Compliance
- Action Level Framework
- Performance
- Other

Standard Map Features

- Buildings
- Solar evaporation ponds
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences
- Rocky Flats boundary
- Paved roads
- Dirt roads

Scale = 1 : 15640
1 inch represents approximately 1303 feet

500 0 1000 2000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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